Instrumentation Division Report

Veljko Radeka

Presentation to the DOE HEP Program Review

APRIL 17-19, 2006

Outline

- **Core Technologies and Facilities**
- **R&D for the Current and Future HEP Program:**

1. **Silicon Detectors**
2. **Gas and Liquid Detectors**
3. **Microelectronics**
4. **Integrated Detectors/Electronics**
5. **LSST**
6. **Lasers and Optics**
7. **Micro/nano fabrication**

Instrumentation Division

Mission:

**"To develop state-of-the-art instrumentation required for experimental research programs at BNL.
To provide limited quantities of such instrumentation for BNL-related experiments."**

Core technologies:

- **Semiconductor detectors** (pixel-, drift-, photo sensors);
- **Gas and noble liquid detectors**;
- **Microelectronics** (low noise analog/digital);
- **Lasers and Optics** (ultra-short photon & electron bunches, photocathodes, optical metrology);
- **Micro/nano Fabrication** (sensors, microstructures, e-beam lithography).

Staff:

46 Total
28 Scientists & Professionals
18, (14+4) Technical & Administrative

Publications in FY 05/06

All Programs: 41

Program 06-10

In support of vital BNL programs:

- RHIC Detector Upgrades (silicon and TPC)
- e-cooler; e-RHIC:

  High Current Photocathodes
- ATLAS Dets., LHC upgrade, ILC
- Si-detectors for Polarimeters
- Si-detectors & microelectronics:

  -EXAFS at high photon rates

  -X-ray Microscopy

  -Protein crystallography

  -TEAM
- LSST
- New small animal PETs, MRI
- Neutron detectors for SNS
- Detectors and Microelectronics for

  Homeland Security Program

State-of-the-art core technology:

- Fine-grained Si and gas detectors
- Low noise microelectronics from submicron to nanoscale
- Femtosecond, photon and particle beam generation & diagnostics
- Nano-fabrication: pattern generation; deposition/ablation; characterization

Exploration:

- CMOS as direct conversion detectors
- Megapixel matrix on kohm cm Si
- Neutrino (“bubble”) detector
- Femtosecond ~100 eV source

R&D for Current and Future HEP Program
(with Physics Dept.)

- Accelerator experiments:
  - LHC/ATLAS, completion, commissioning
  - LHC upgrade, detector and electronics technologies (e.g., rad. hard silicon detectors silicon-germanium microelectronics)
  - ILC detectors
  - ILC photocathode R&D and beam diagnostics

- Non-accelerator experiments
  - Dark energy (LSST with SLAC)
  - Neutrino dets. (< 200 keV threshold, with Columbia Univ.)

R&D at BNL for ILC (with Physics Dept.)
I. Detectors

1. ***Monolithic Active Pixel Sensors (MAPS) for Vertex Detection.***

   This is based on direct collection of charge produced by an ionizing particle within the sensitive layer of a CMOS readout circuit. The result is a low mass (~0.1% of radiation length of Si) detector layer with a position resolution of a few microns.

2. ***Fine granularity small TPCs.***

   These TPCs will be based on GEMs (Gas Electron Multipliers) at the ends of the drift region followed with fine granularity interpolating readout electrodes and extensive use of monolithic circuits designed for low noise TPC waveform recording.

3. ***EM – calorimetry based on tungsten absorbers and silicon sampling layers (in collaboration with M. Breidenbach, et al., SLAC, as a part of SiD collaboration).***

   Fine granularity calorimetry with small cells (~ 5 mm) can only be realized with *in situ* readout at the sampling layers. This requires specially designed monolithic circuits and presents interconnection topology challenges.

4. ***End cap calorimetry (with W. Morse et al., Physics Dept.)***

   Silicon detectors, radiation effects on silicon, readout eletronics.

R&D at BNL for ILC
II. In Support of Accelerator Technology
(with Physics Dept., CAD, SMD)

1. ***Photocathode development for polarized electron beams:***

    1.1 Development and testing of a low emittance ellipsoid beam using suitably designed laser beam;

    1.2 Development of a long lived photocathode and characterization of the polarized electrons;

    1.3 Integration of laser, cathode injector and magnet system to produce and characterize the electron beam for the ILC:

    - generation of flat beam;
    - generation of low emittance;
    - production of polarized beam of required charge, bunch structure and life time.

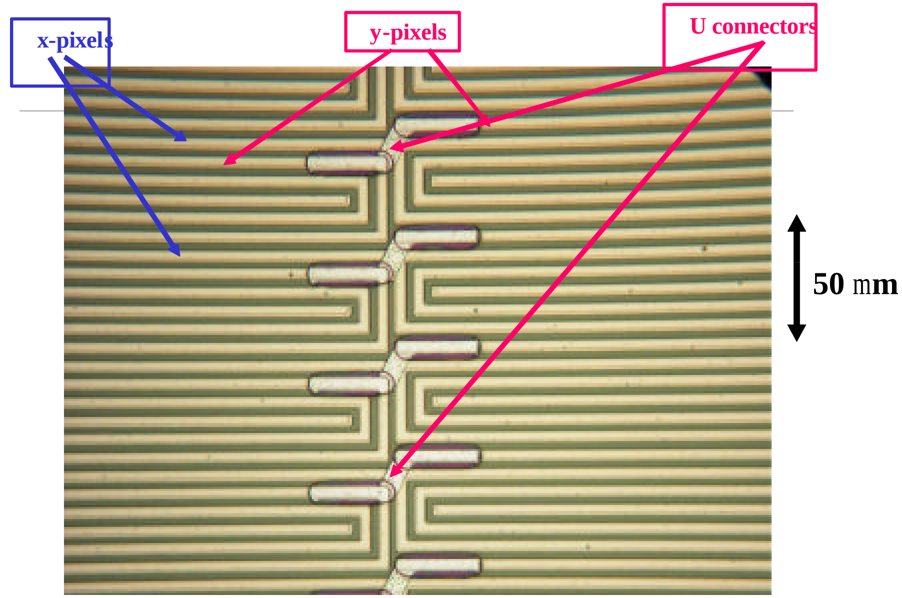
2. ***Electron beam profile and bunch length diagnostics.***

    Physics Dept., CAD and Instrumentation Division have been working on using electro optic technique to measure the bunch length of relativistic electron beams with sub ps time resolution, which is essential for characterization of ellipsoidal beams.

1. Silicon Detectors

2d Stripixel detectors for US-ATLAS Upgrade (radiation hard up to 2x10^{15} n_{eq}/cm^2). *Starting point: Stripixel dets. developed for PHENIX/RIKEN, and transferred to Hamamatsu.*

- ***Combination of 3 new aspects*:**
  - ✓ **2d stripixel structure with short strips (3 cm)**
  - ✓**P-type substrate (no inversion, 1-sided process, higher CCE than n-type after radiation)**
  - ✓**Magnetic Czochralski-Si (MCZ-Si) for added radiation hardness**
  - ✓**Radiation tests are planed and underway**



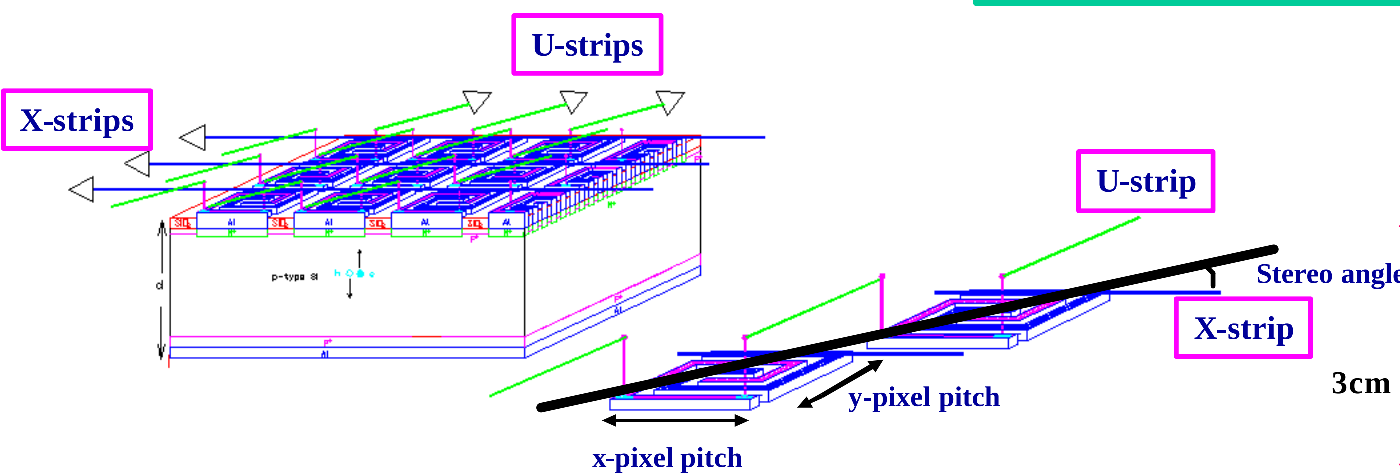
US-ATLAS Upgrade test layout:

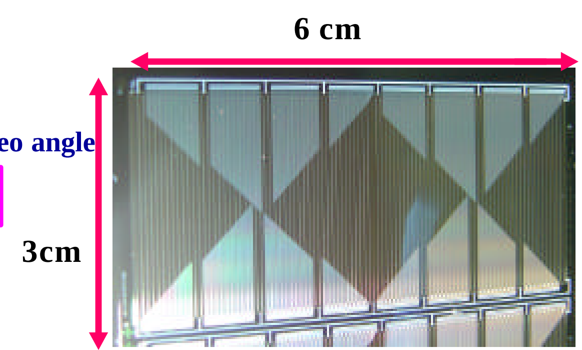
Pixel pitch: 620 mm (X) and 50 mm (Y)

Strip pitch: 50 mm (U) and 50 mm (X)

Stereo angle between u and Y strips: 4.6 º

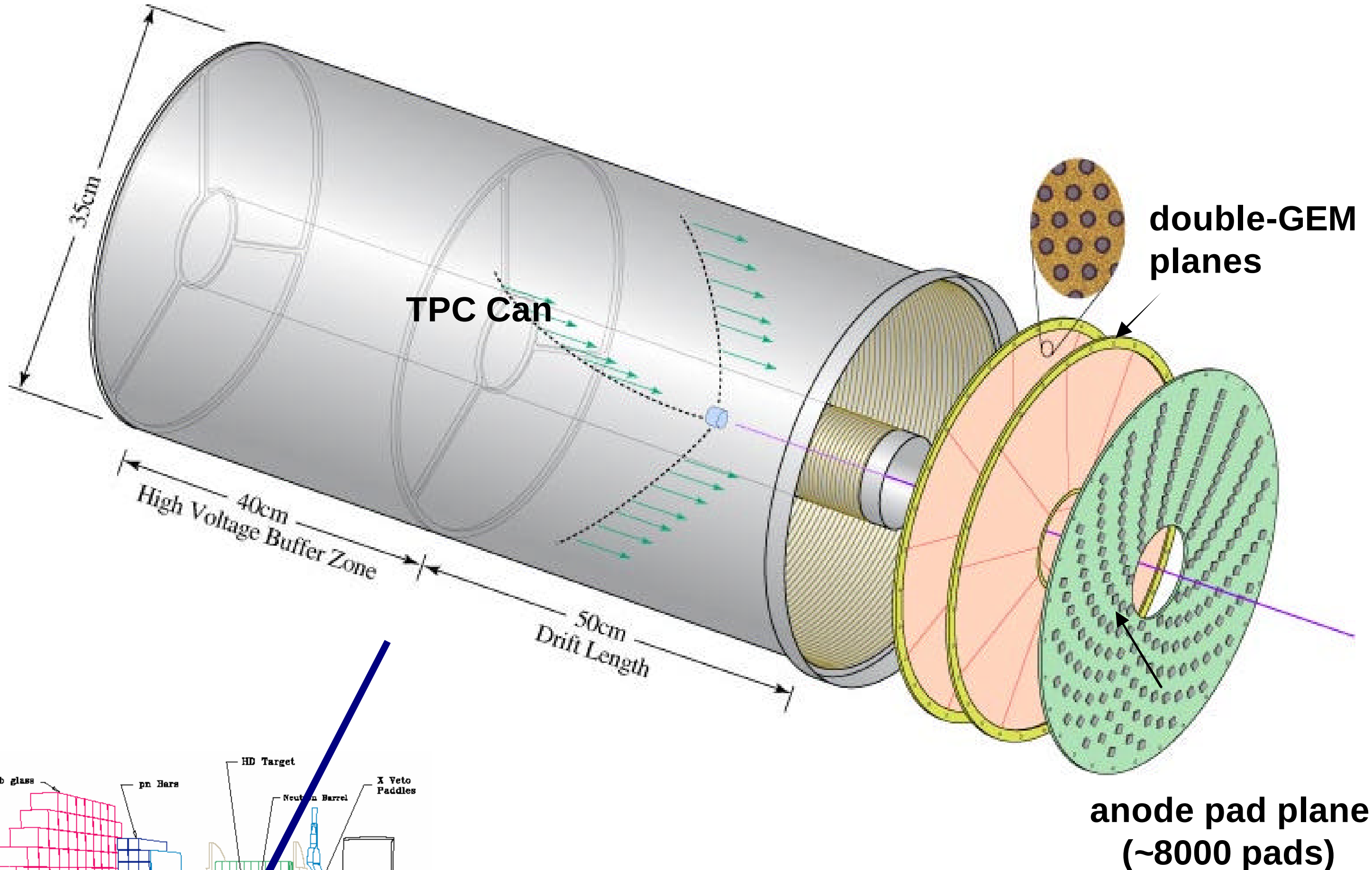
MCZ p-type, detector thickness 200-300 mm

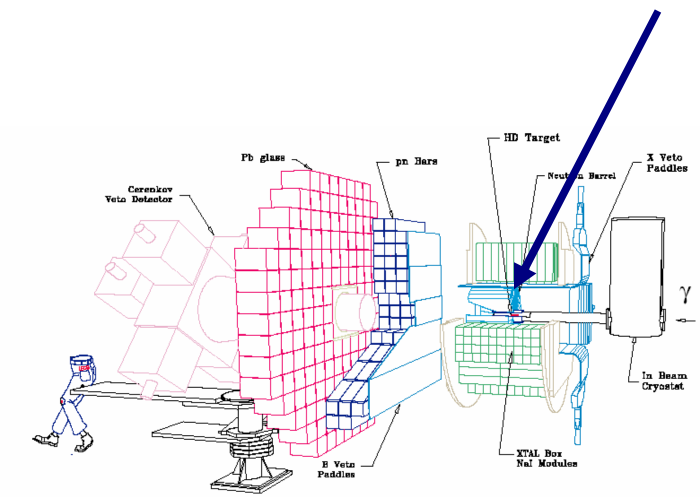




2. Gas and liquid detectors

Time Projection Chamber (TPC) for Laser Electron Gamma Source (LEGS)

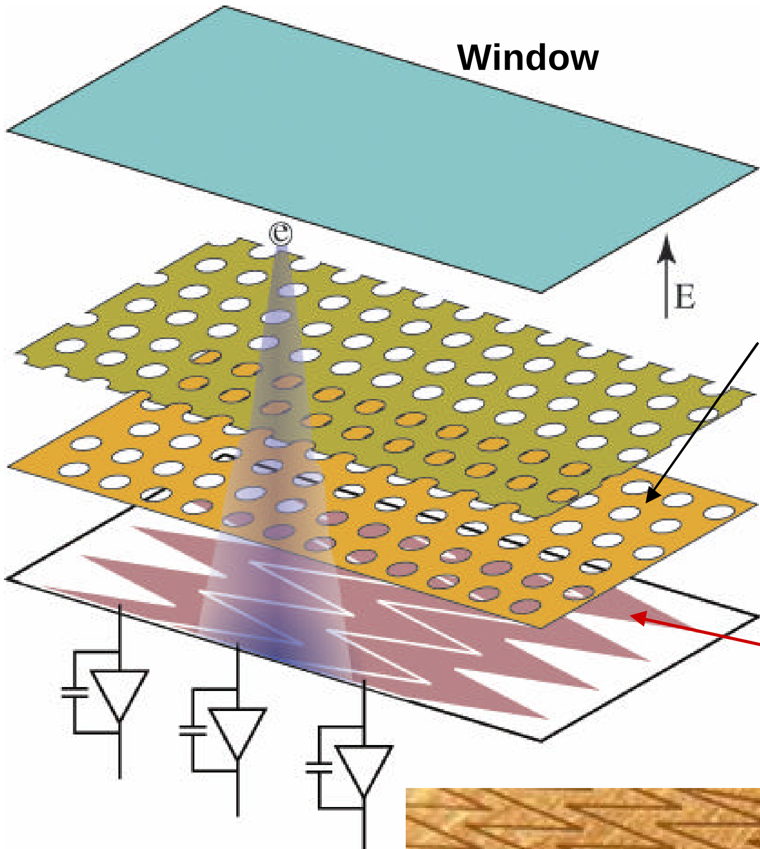


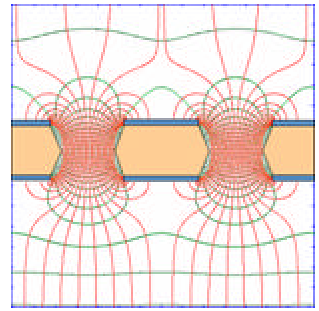


Spin **ASY**mmetry Array (SASY)

Fine granularity TPC technology of interest for: RHIC/PHENIX and Linear Collider

Interpolating Pad Readout for Gas Electron Multiplier (GEM)

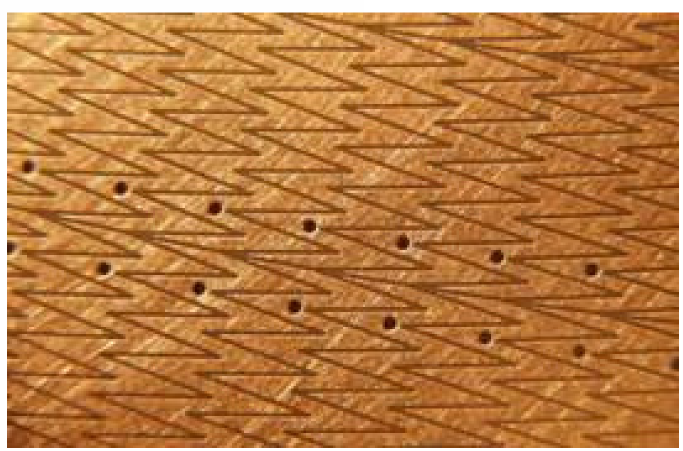




1st GEM

2nd GEM

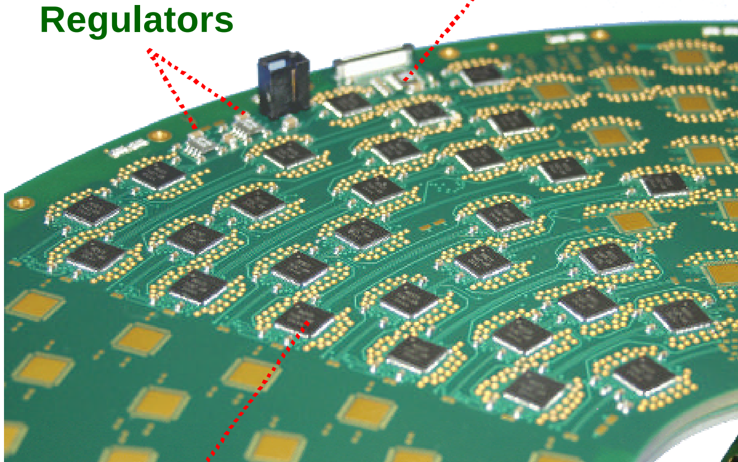
Anode Pad Plane

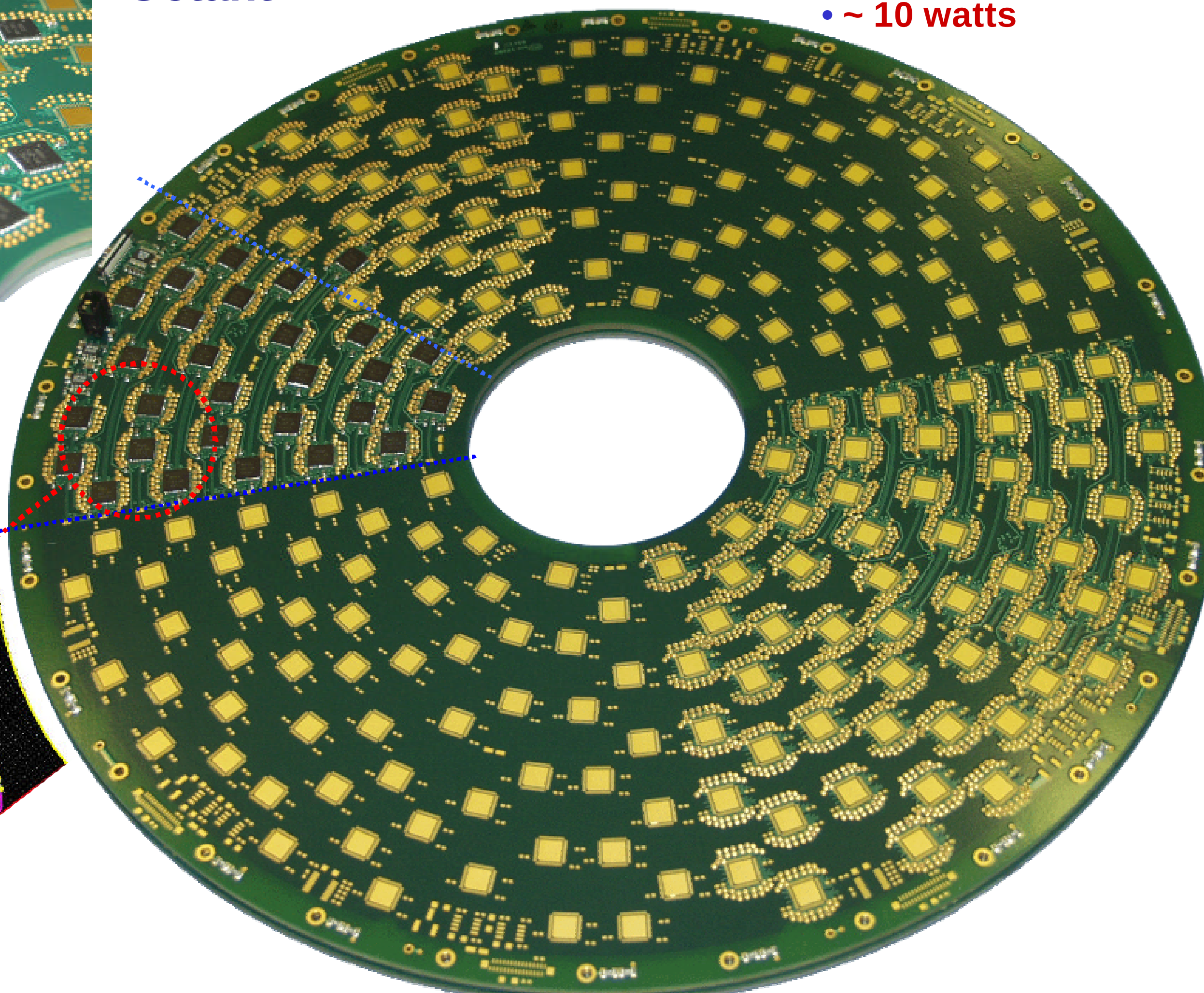


Mounted GEM Foil on Frames

Completed End Cap:
GEMs+pad plane+electronics

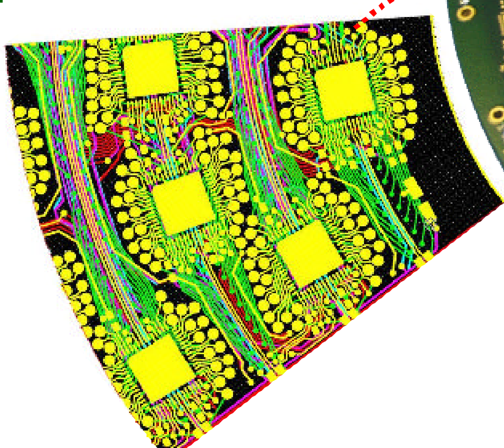
Readout Electronics (Back of Pad Plane)



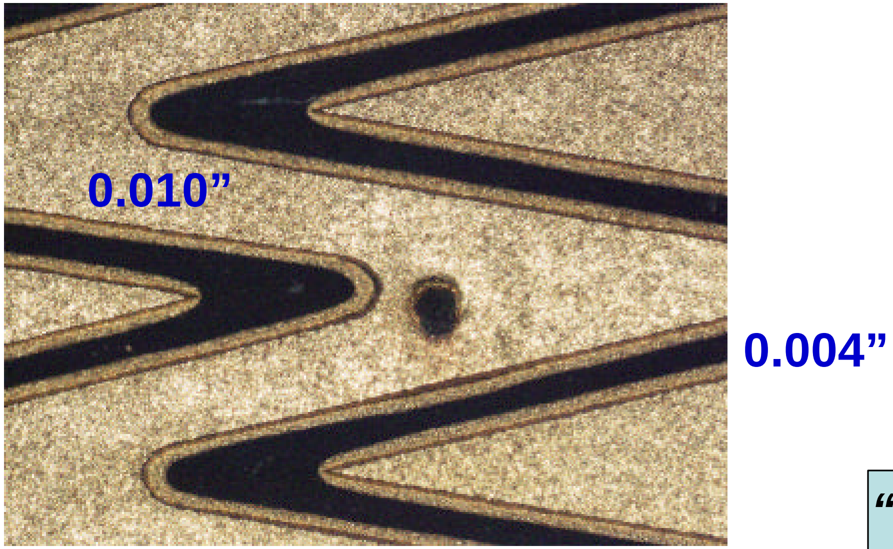


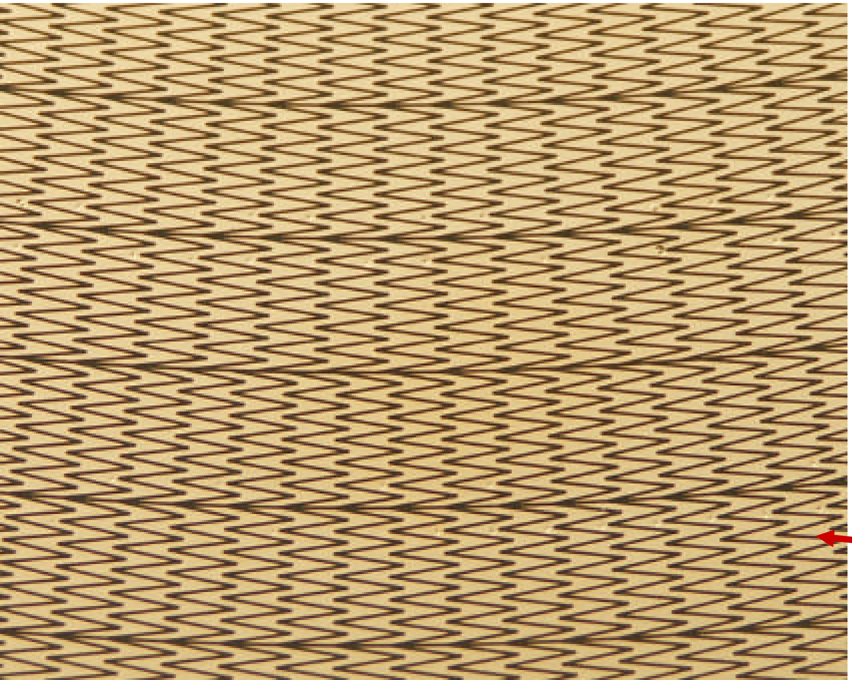
Full Board
- 228 ASICs
- 7296 pads
- 1346 components
- ~ 4000 standard vias
- ~ 8000 *blind* vias
- ~ 8500 signal nets
- 11 layers
- ~ 10 watts

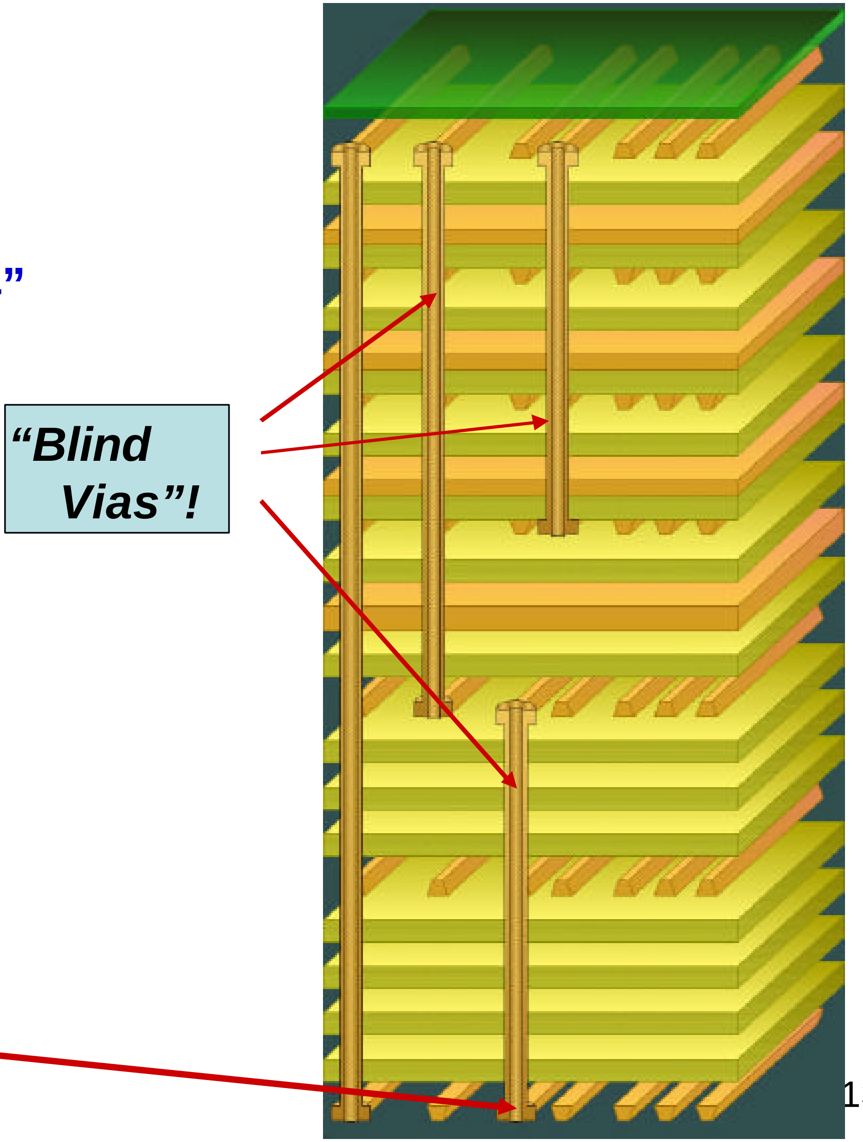
ASICs
- ~ 30 ASICs / octant
- 32 channels / ASIC
- ~ 1.2mW / channel
- energy/timing per channel
- token/flag sparsified readout



Anode Pad Plane – Asic Board: *A major topology and fabrication challenge (solved: A. Kandasamy report)*

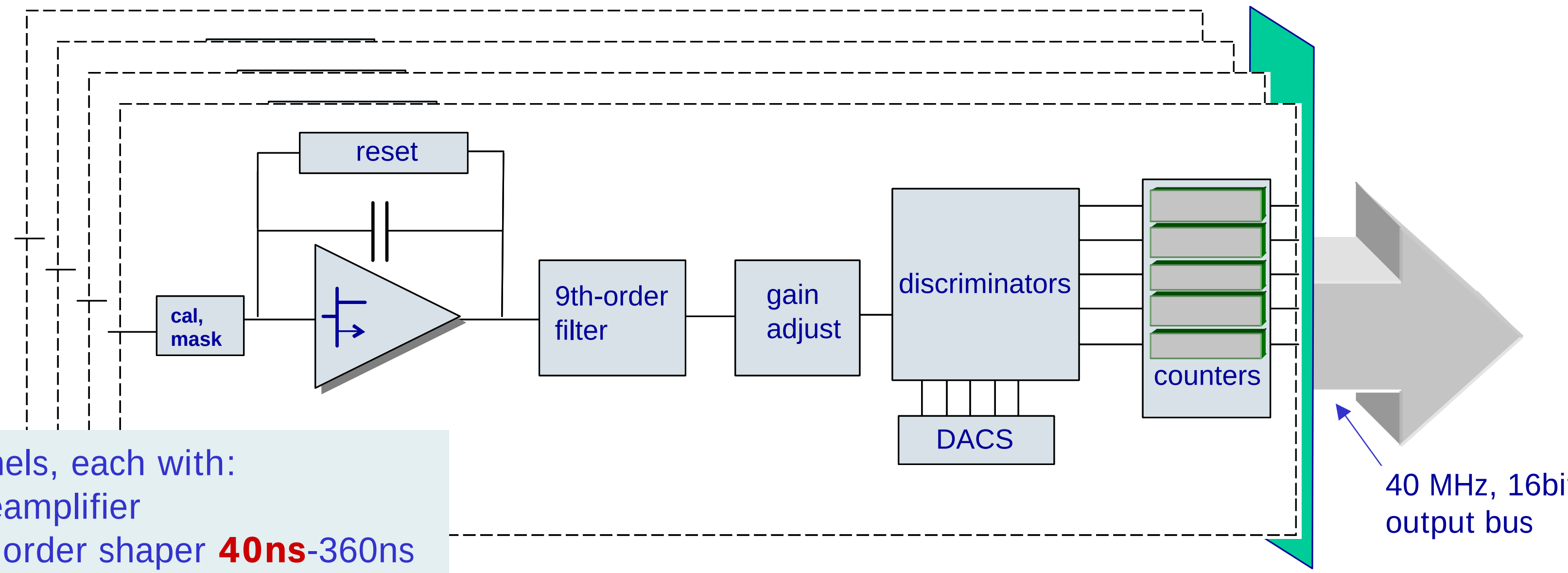




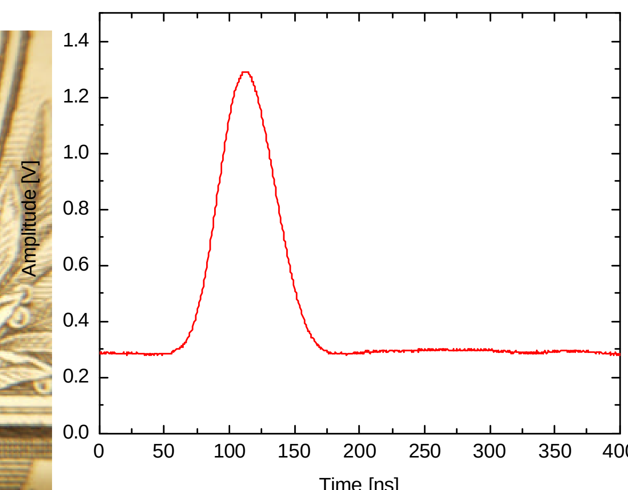


3. Microelectronics

ASIC for Multi-Window High-Rate Counting – CZT and Si X-ray Dets.



- 64 channels, each with:
  - preamplifier
  - 9th order shaper **40ns**-360ns
  - settable coarse gain 250mV-1V /fC
  - 5 x (discriminator + 16-b counter)
  - MHz count rate capability
- zero deadtime (shadow memory)
- five 10-bit DACs for thresholds
- 2048 registers
- analog monitors with output buffer
- 0.25µm CMOS, 5 mW/channel
- ***600,000*** **MOSFETs in 6.6 x 6.6 mm²**



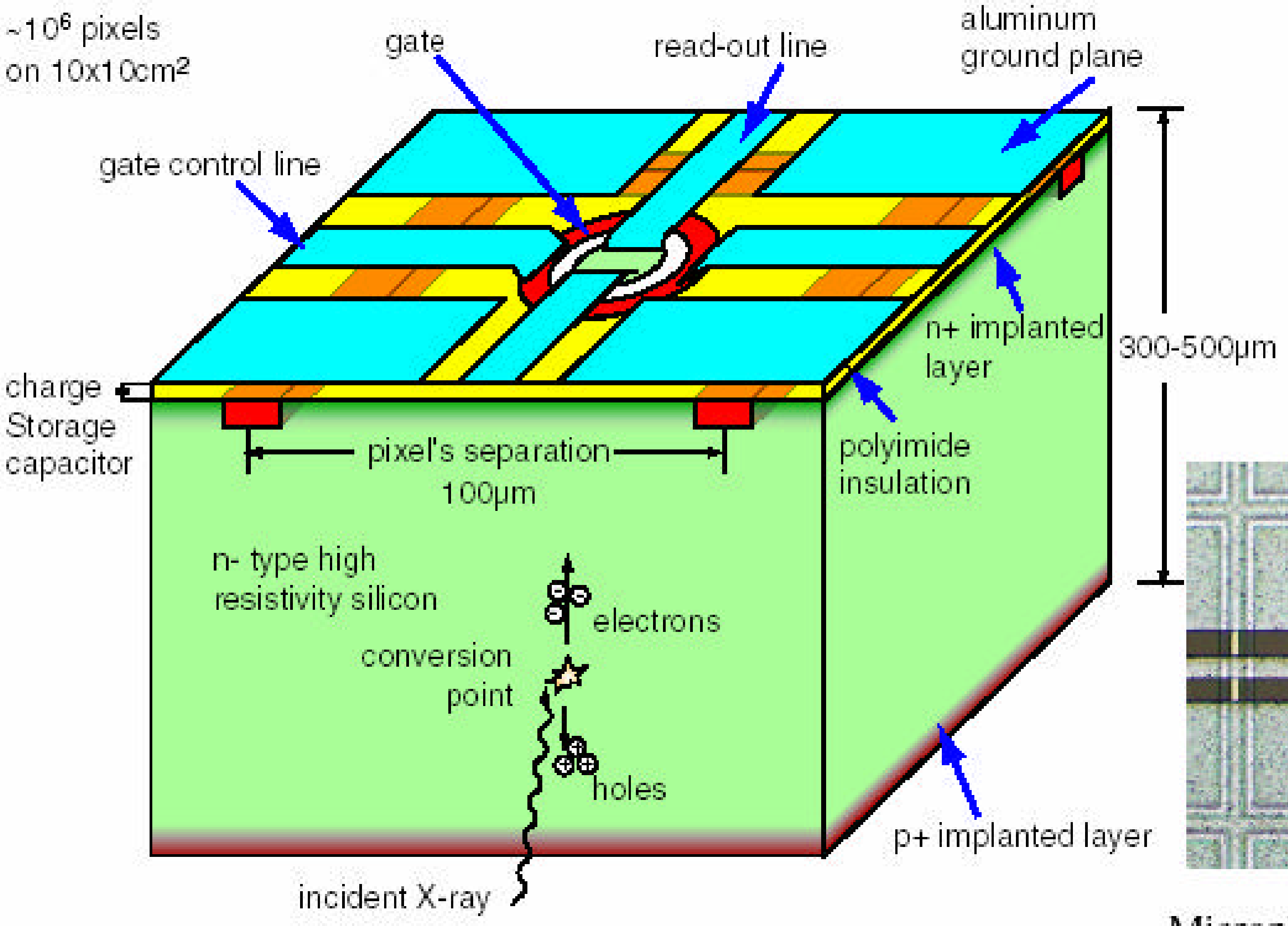
4. Integrated Detectors/Electronics:
"Detectors and Transistors on the Same Chip"

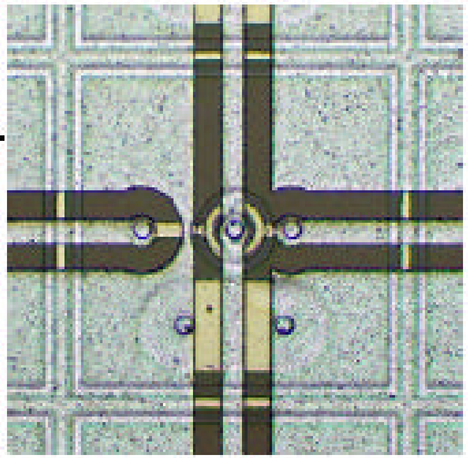
- *Transistor on high rho (10 kohm cm) Si*

- *Detection in standard CMOS (~10 ohm cm epi Si)*

"Transistor on high rho (~10 kohm cm) Si":

3D View of an X-ray Active Matrix Pixel



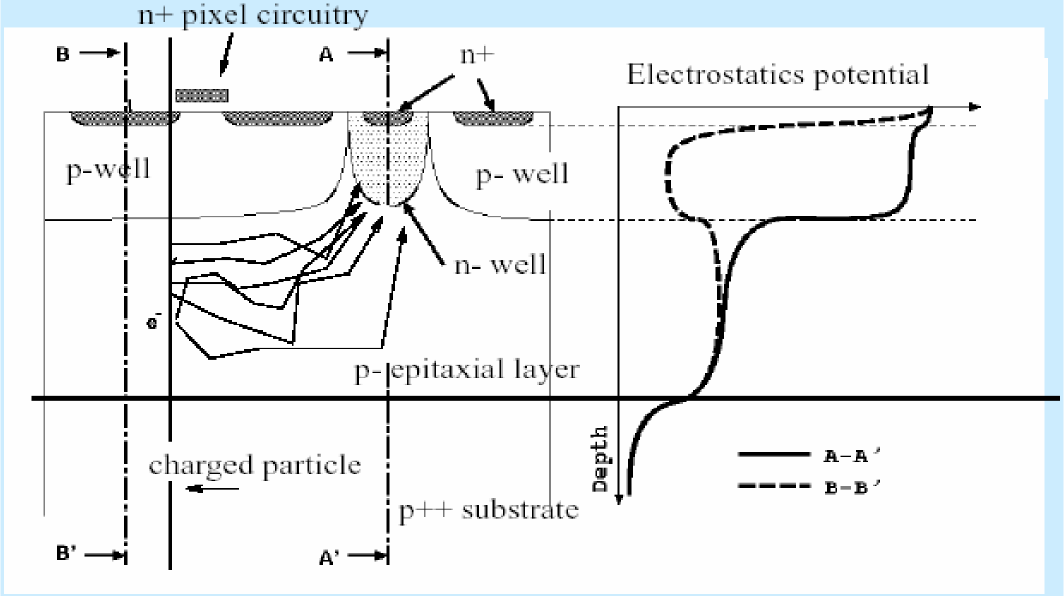


Microphotograph of a pixel

CMOS as Direct Conversion Megapixel Detectors (10-20 µm pixels) ? Monolithic Active Pixel Sensors (MAPS)

Epitaxial layer ~5-15 µm

Min. ion. particles ~80 e/µm



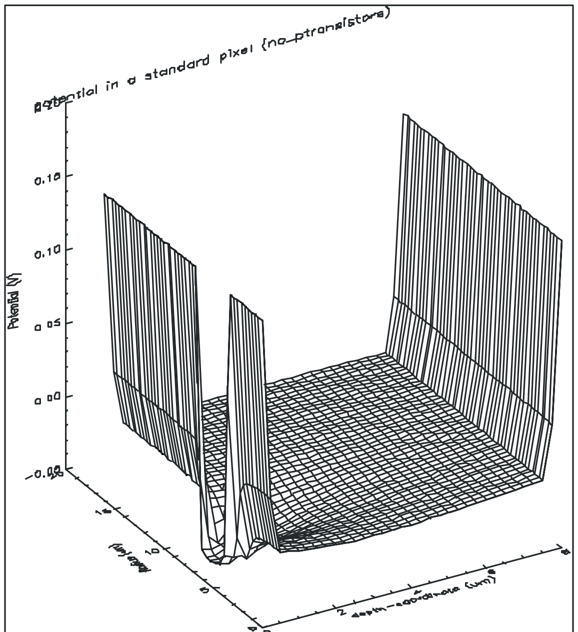
Twin - tub (double well), CMOS process with epitaxial layer

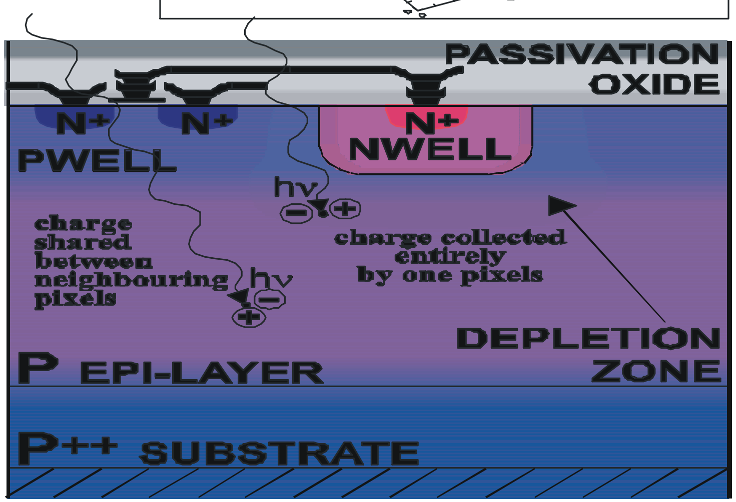
A problem:

Charge collection by diffusion ? ~ 500 e signal spread on several pixels, ~200 ns collection time

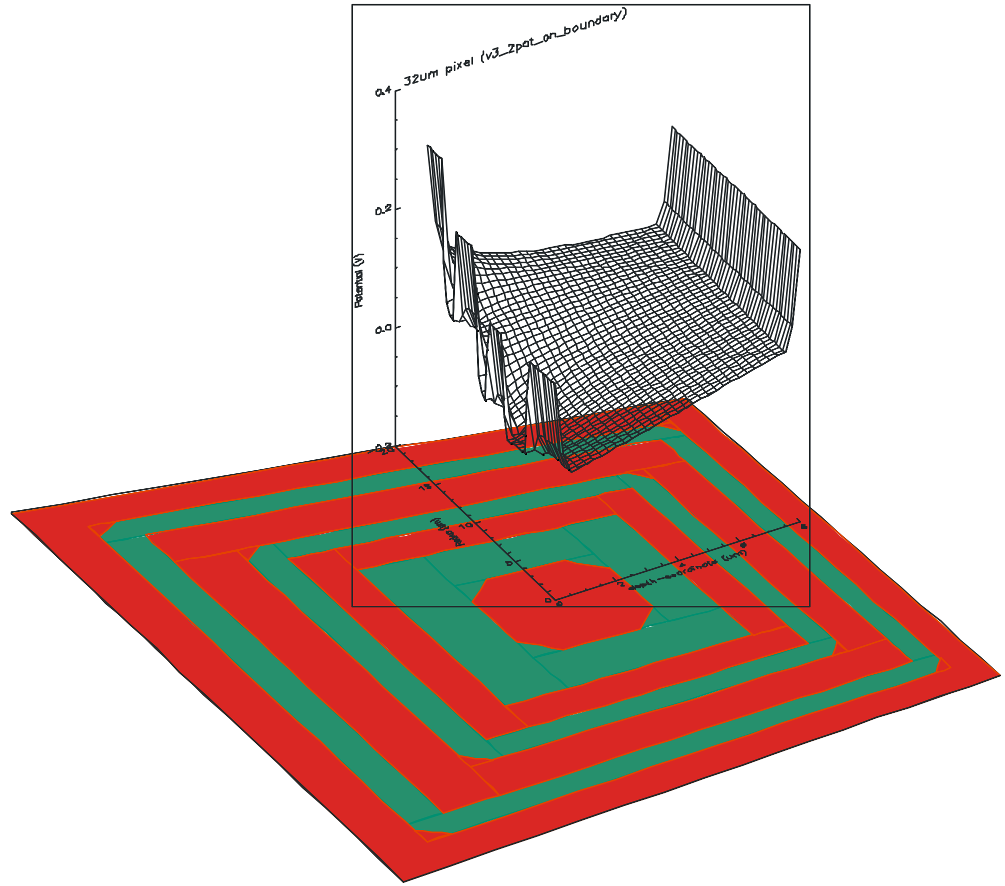
- The effective charge collection is achieved through the thermal diffusion mechanism,
- The device can be fabricated using a standard, cost-effective and easily available CMOS process,
- The charge generated by the impinging particle is collected by the n-well/p-epi diode, created by the floating n-well implantation,

Original MAPS:
(Deptuch,Turcheta, et al.)





A new concept - and challenge: introduce a ***drift field*** into standard CMOS process (Rehak, et al.)



View of a pixel

- ***Green*** are n-wells for anode and p-channel transistors
- ***Red*** are p-wells fo n-channel transistors

5. LSST

Physics Dept and Instr. Div.

Jim Frank

John Haggerty

Morgan May

Zheng Li

Paul O'Connor

Veljko Radeka

Peter Takacs

+ Instr. Infrasructure

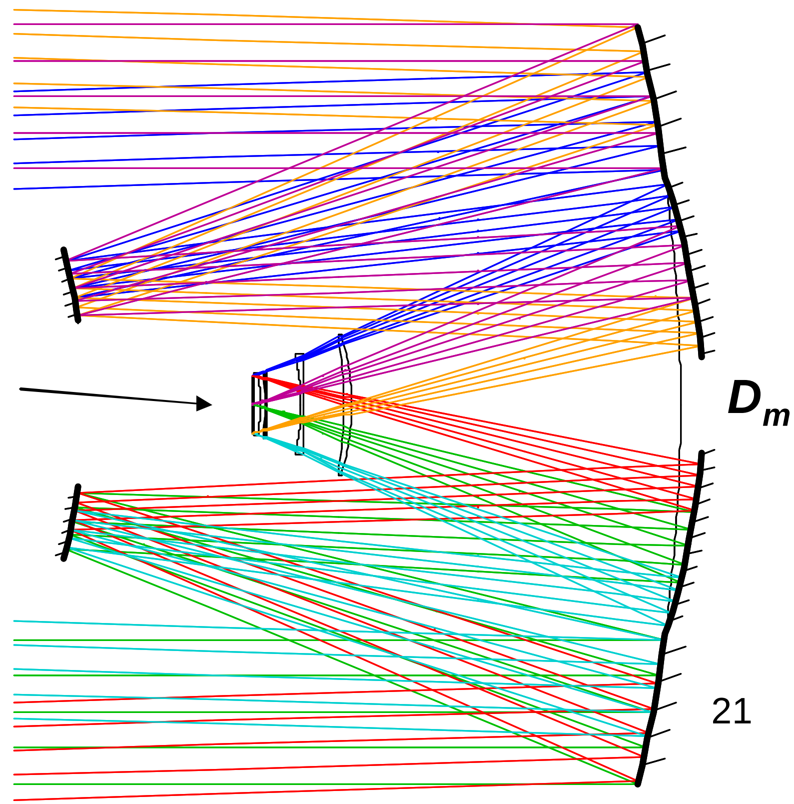
"Large Telescopes"

		Survey telescope	Deep probe
• Primary Mirror	*dia*.=D_m, *Area*= ***A***	***Large (~8m)***	***Very large (~30m)***
• ***f***-number	***f /#***	***~ 1/1.2***	***~ 1/30-40***
• Focal Plane Array *dia*.= D_f		***Large (~60cm)***	***Medium (~20cm)***
• Field of View	***O a*** D_f / D_m	***~3-4 degrees***	***~20 arc min***
• ***Etendue***	***AO***	***~330m²deg²***	
• Plate Scale	arcsec/µm	***0.02***	

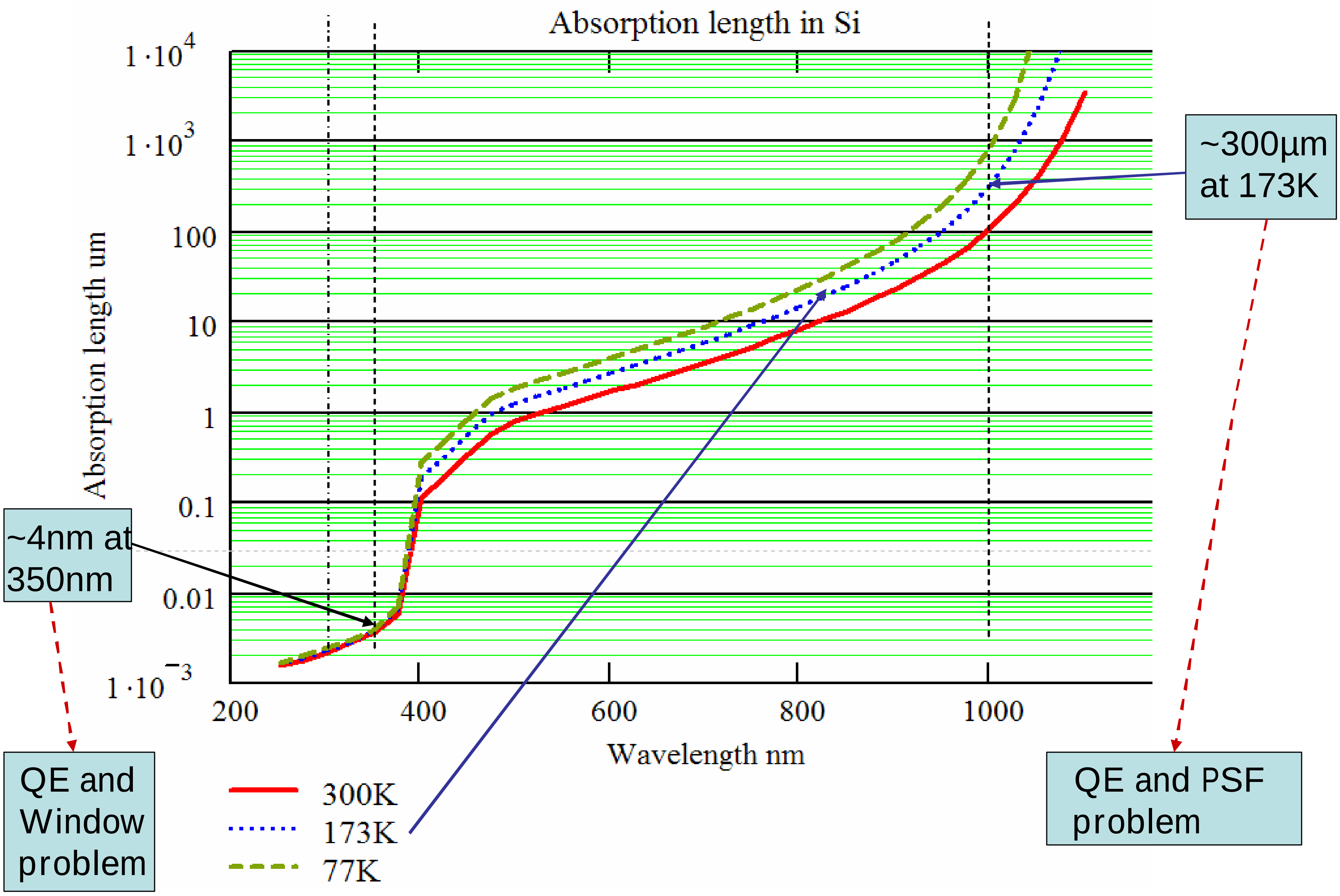
Science Drivers: Wide area surveys for dark energy studies

FPA Requirements: ~**$3x10^9$ 10µ m pixels**

- Increase Area
- Increase QE in near IR
- Reduce PSF (diffusion and pixel size)
- Increase readout speed

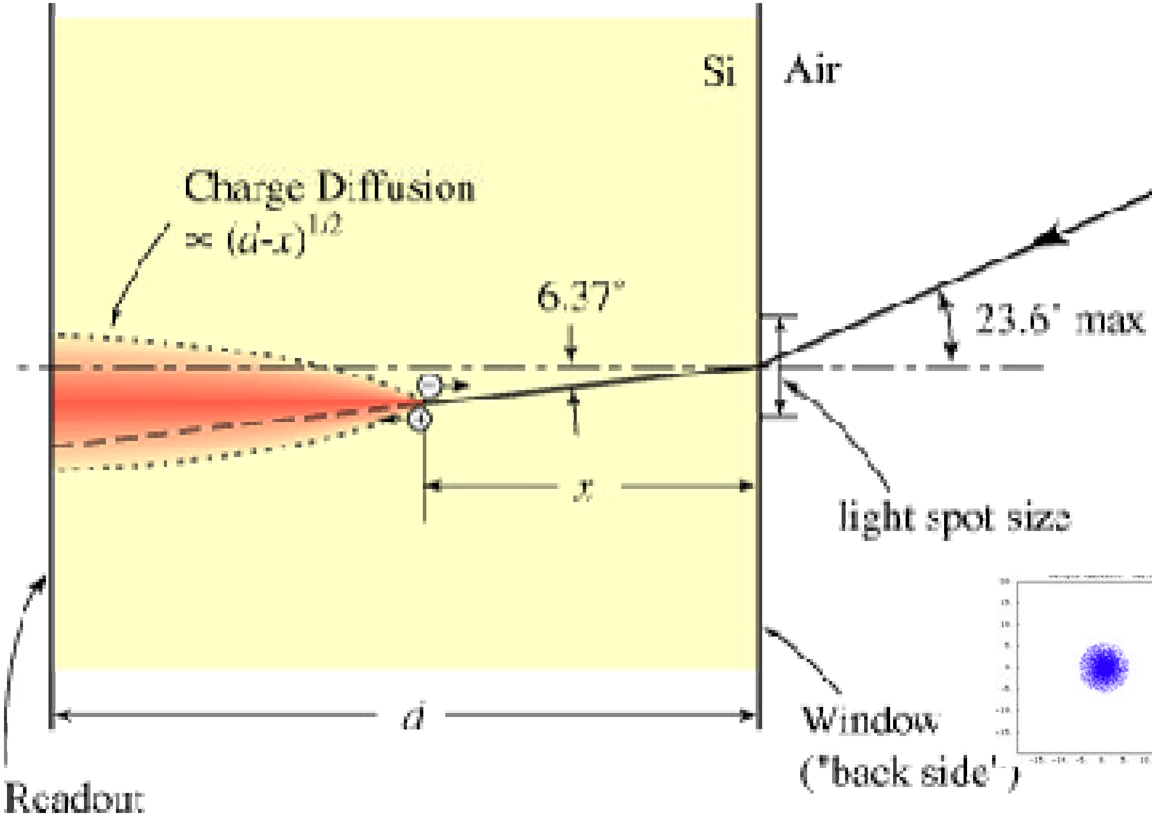


Sensors: *BNL responsibility*
Camera: SLAC "

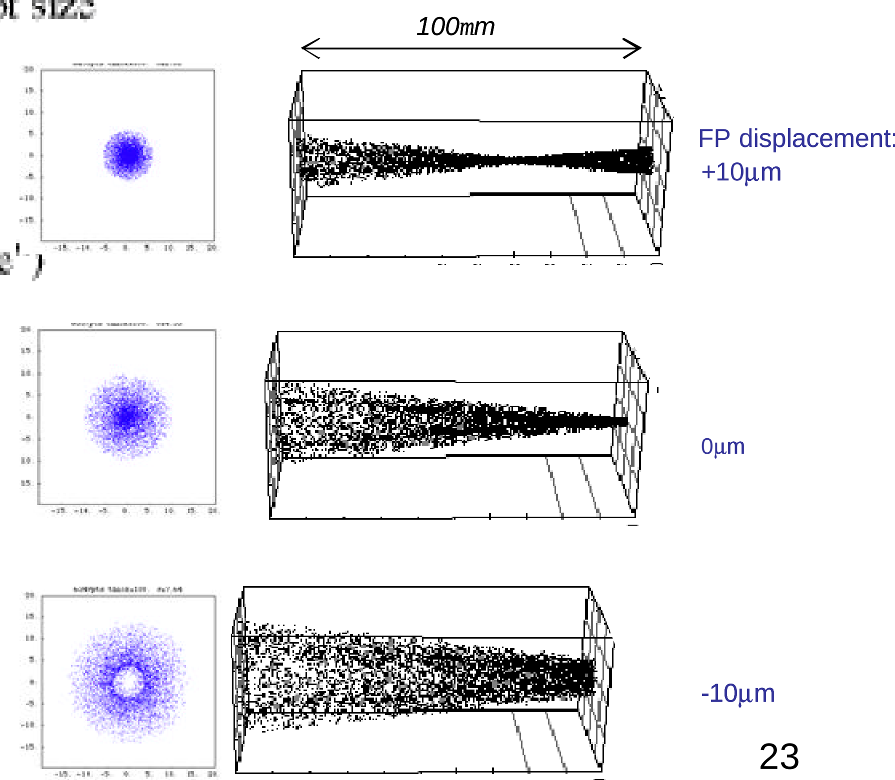


Absorption length in Si
Absorption length um
Wavelength nm
$1 \cdot 10^4$
$1 \cdot 10^3$
100
10
1
0.1
0.01
$1 \cdot 10^{-3}$
200
400
600
800
1000
300K
173K
77K
~300µm at 173K
~4nm at 350nm
QE and Window problem
QE and PSF problem

Point Spread Function (PSF) in Si

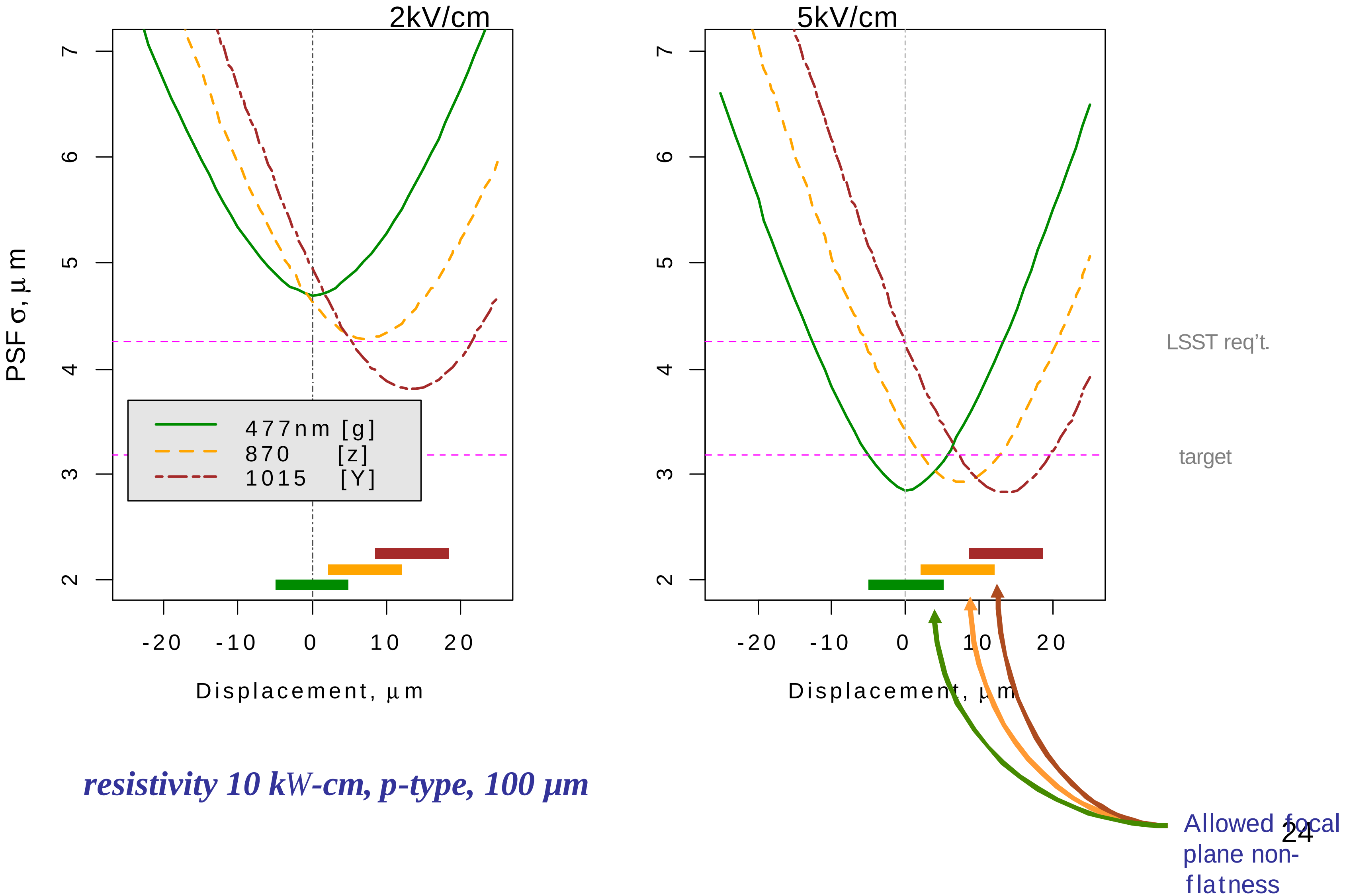


Simulation by P. Takacs, BNL:



Light spot, cone, absorption? ionization, charge diffusion ? PSF

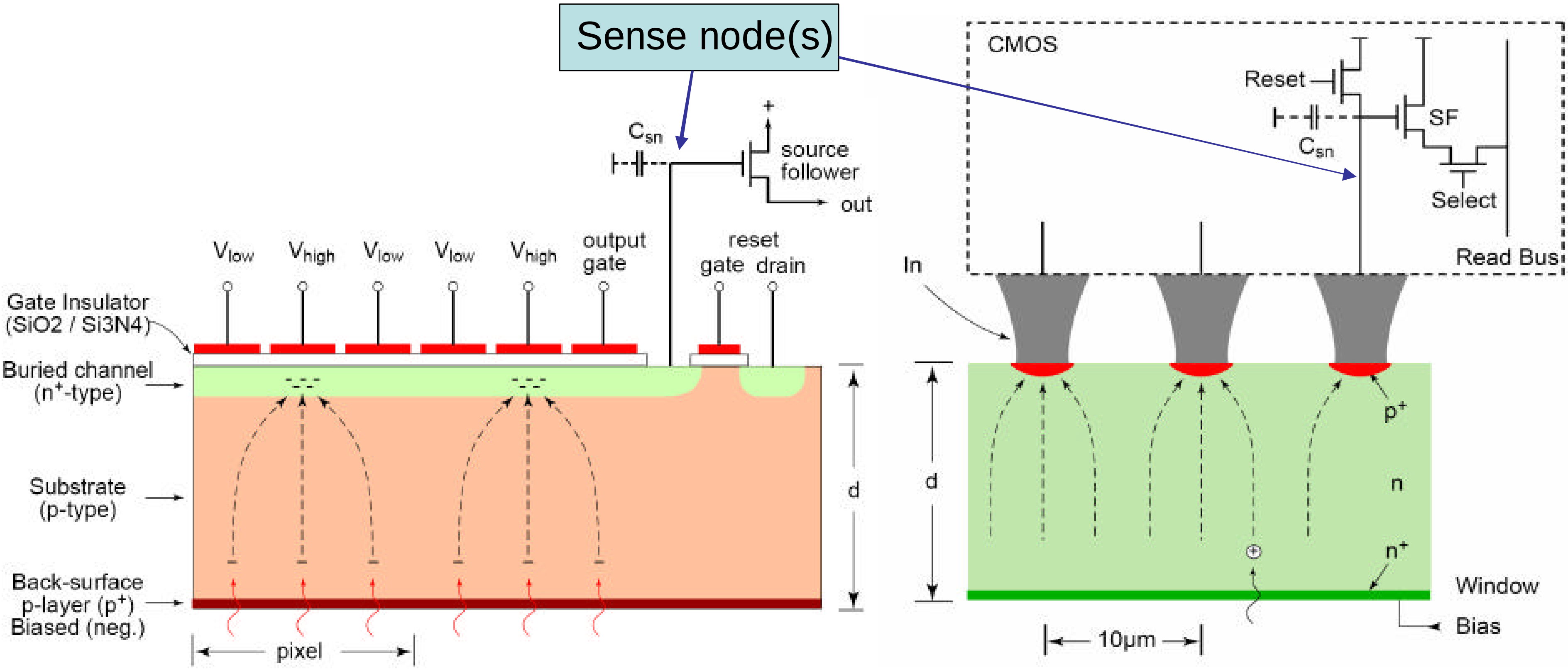
Optimal focal plane position varies with wavelength due to divergence of f/1.2 beam



resistivity 10 kW-cm, p-type, 100 µm

CCD

Hybrid PIN-CMOS



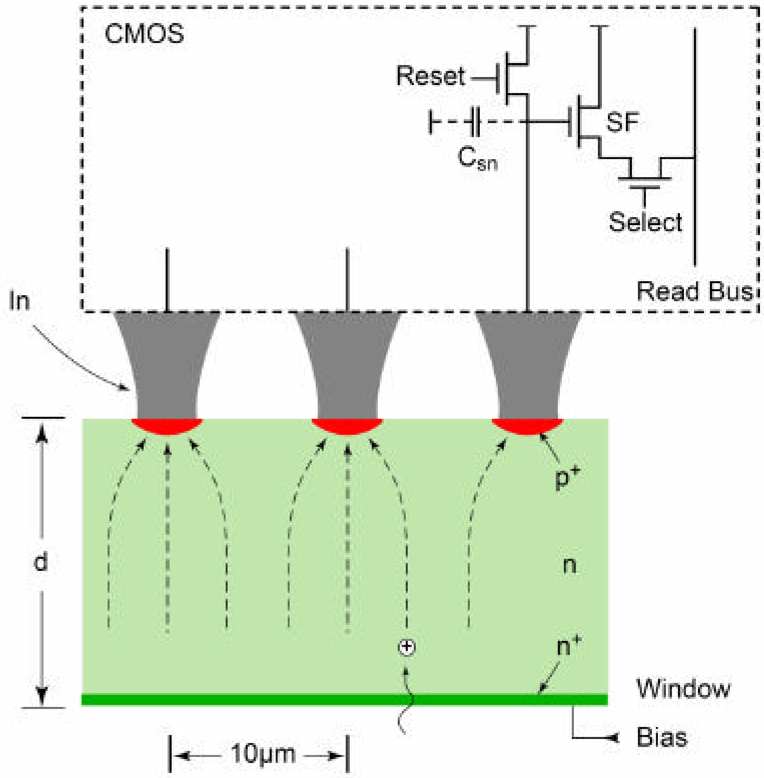
•In a CCD, the signal charge is transferred ***serially*** by a noiseless process (very high CTE) to ***a single sense node,*** where it is converted to a signal voltage.

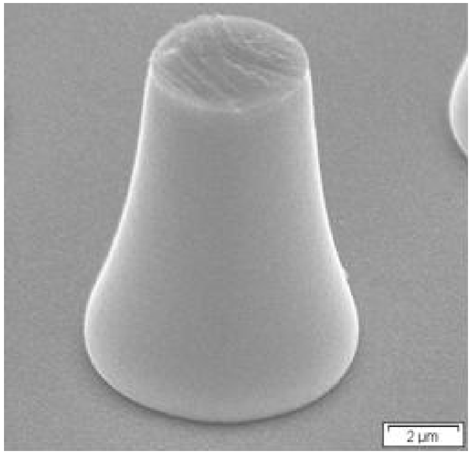
•Pixels are read out ***after*** the integration is completed.

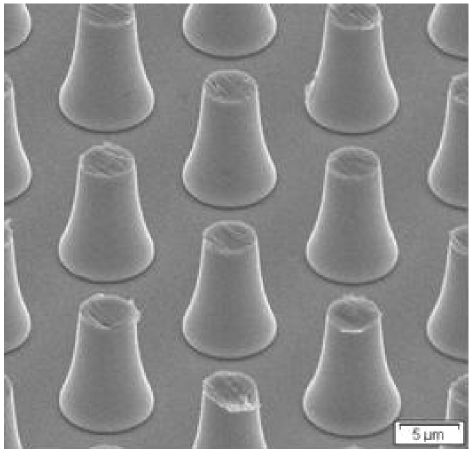
•In a PIN CMOS sensor, the charge to voltage conversion takes place ***in parallel at the sense node of each pixel***.

•The signal voltage can be read out "up the ramp" ***during*** integration.

Indium Bump Bonding

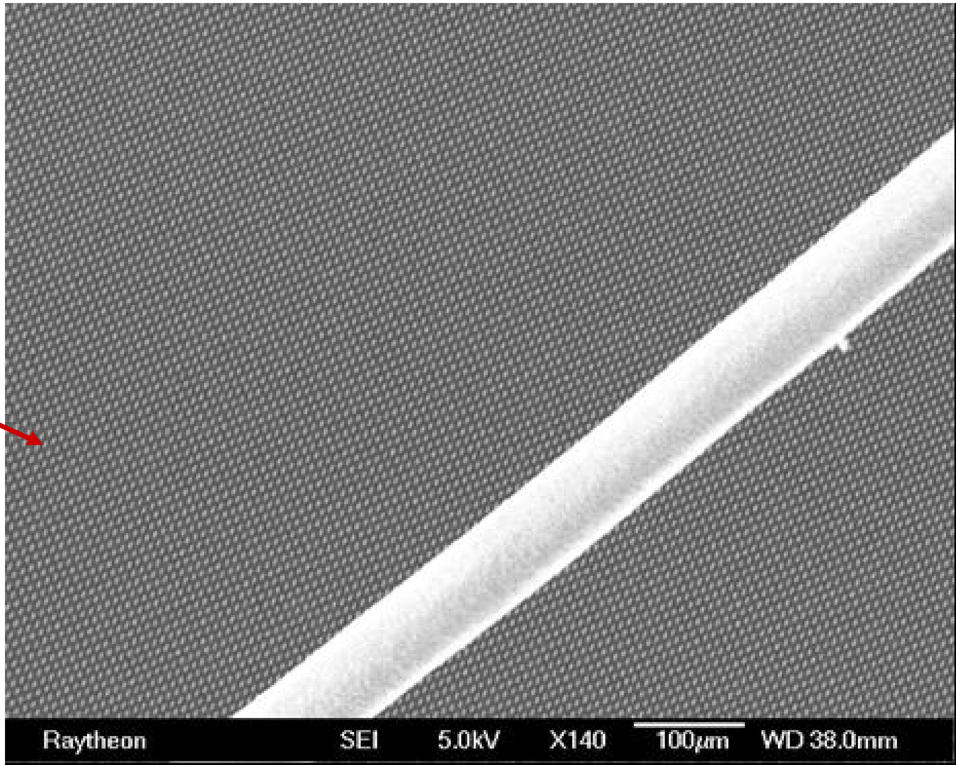






Bond yield by RVS and RSC >0.999

~$1.5x10^6$/cm^2

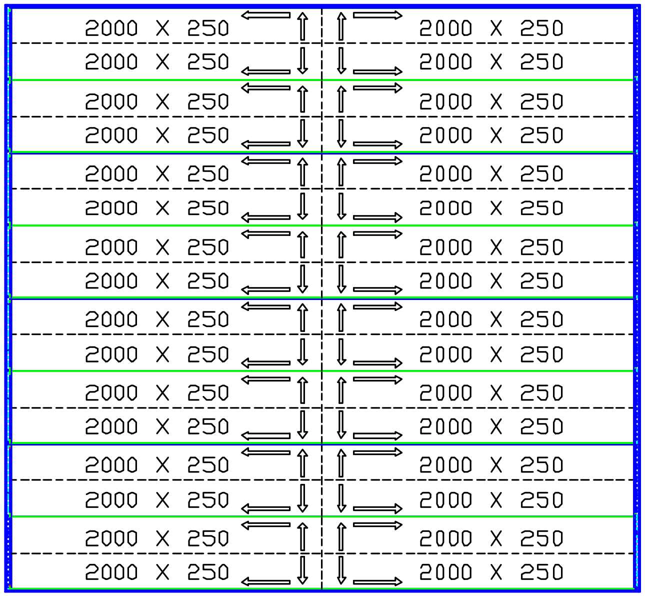


Indium interconnect array on 8 um centers compared to a human hair.

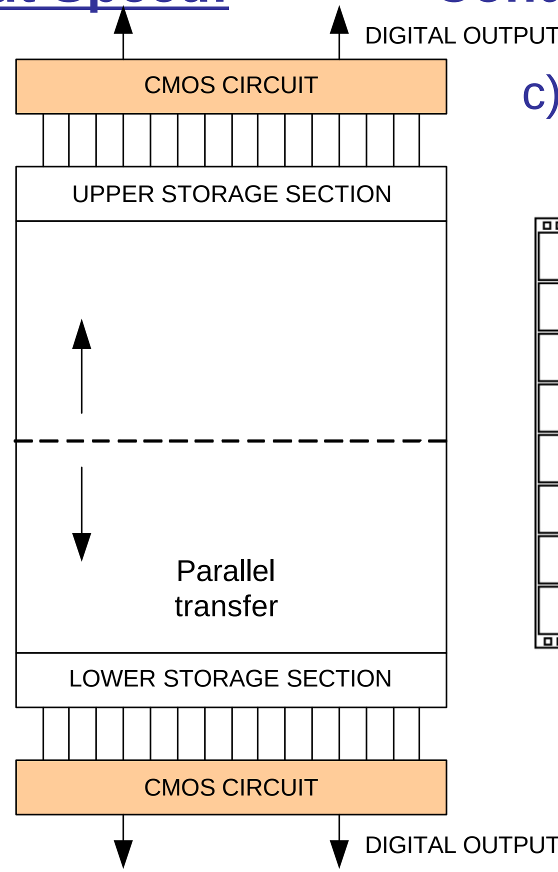
From: K.T. Veeder et al., "Enabling Technologies for Large Hybrid Focal Plane Arrays with Small Pixels", Raytheon Vision Systems

Segmenting CCDs for Readout Speed: Condition: < 5 e rms

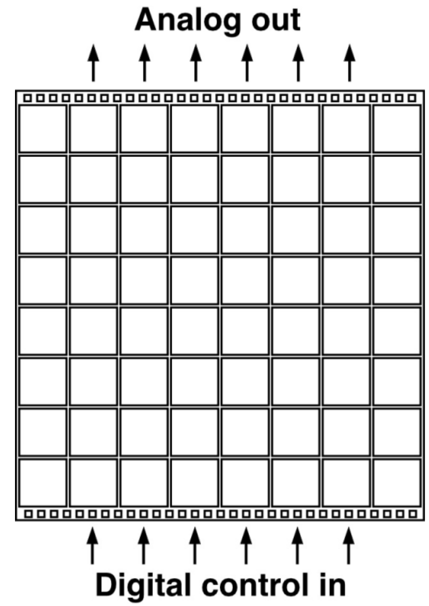
a)



b)



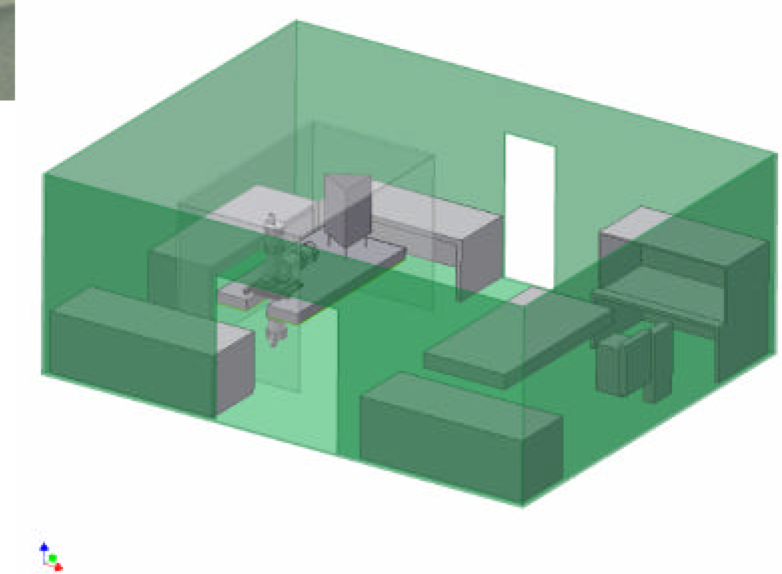
c)

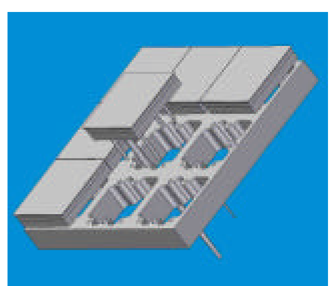


All arrays 4kx4k=16 Mpixels

	a)	b)	c)
Segments:	Up to 32	Up to 2x4k!	64 (or more)
Advantages:	Short columns – -*blooming localized*	High frame rate	Combination of a) and b) if not an OTA
Disadvantages:	*Non-contiguous imaging* due to serial registers	Long columns (*blooming*)	Density of outputs too low for direct bump bonding to CMOS readout
Application:	LSST-like telescopes	X-ray detectors	
Source followers:	*on* CCD	*On* or *off* CCD	On CCD (Pan STARRS), or off

Development Followup, Device Modelling, Sensor Evaluation and Testing

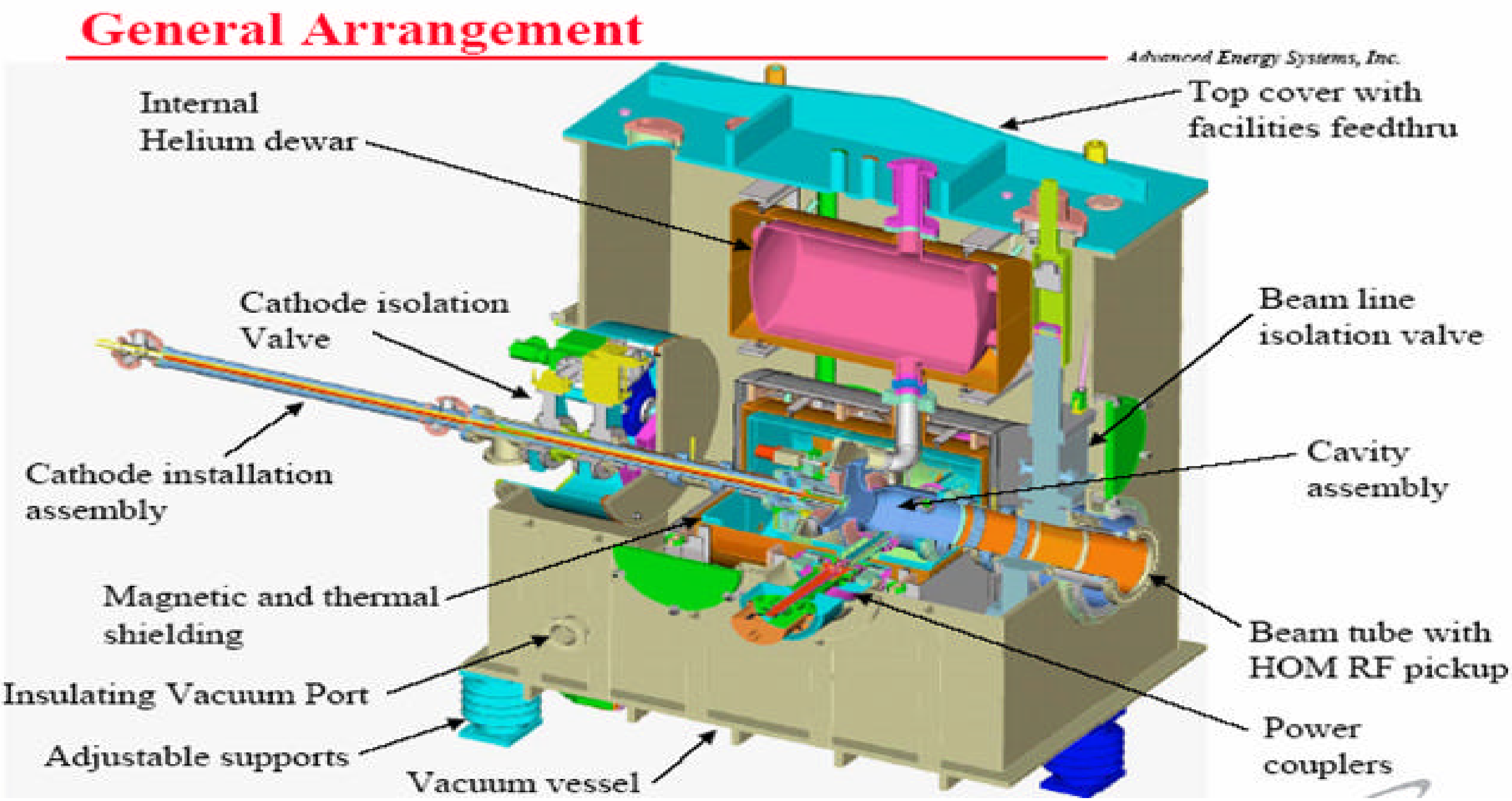




- Design and progress reviews under Study Contracts;
- Modelling of special semiconductor device design issues (guard rings, edge areas, independent biasing, crosstalk, diffusion, etc.);
- Electrical testing;
- PSF measurements
- Optical metrology for sensors and 3x3 rafts
- Clean lab with interferometers, ...

6. Lasers and Optics

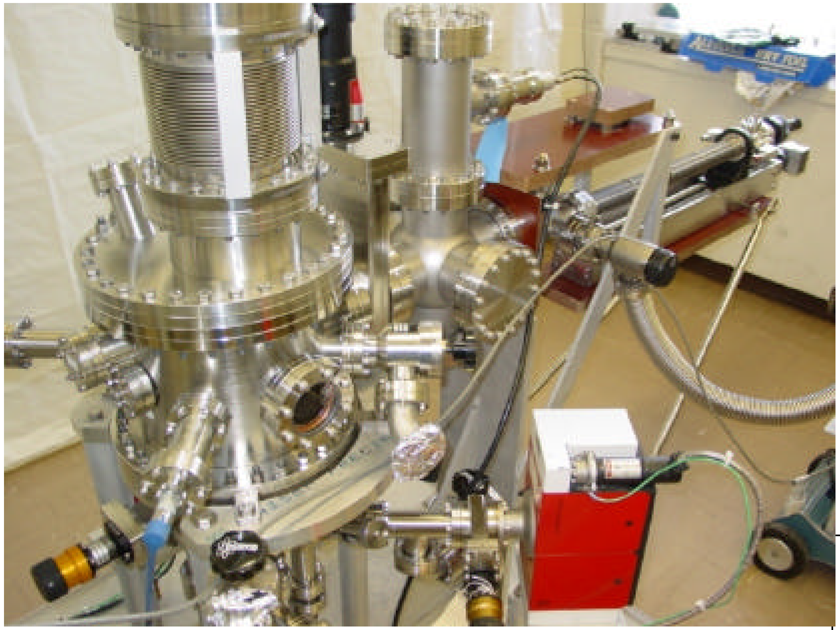
High Brightness, High Average Current Electron Sources

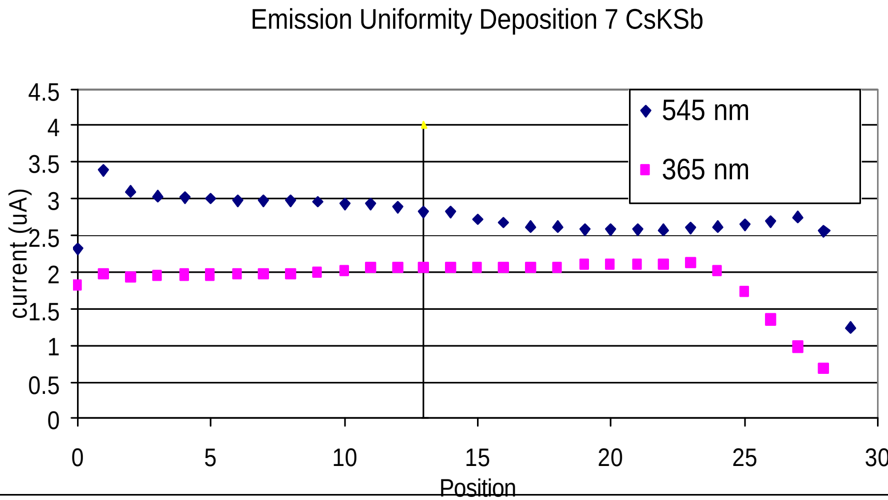


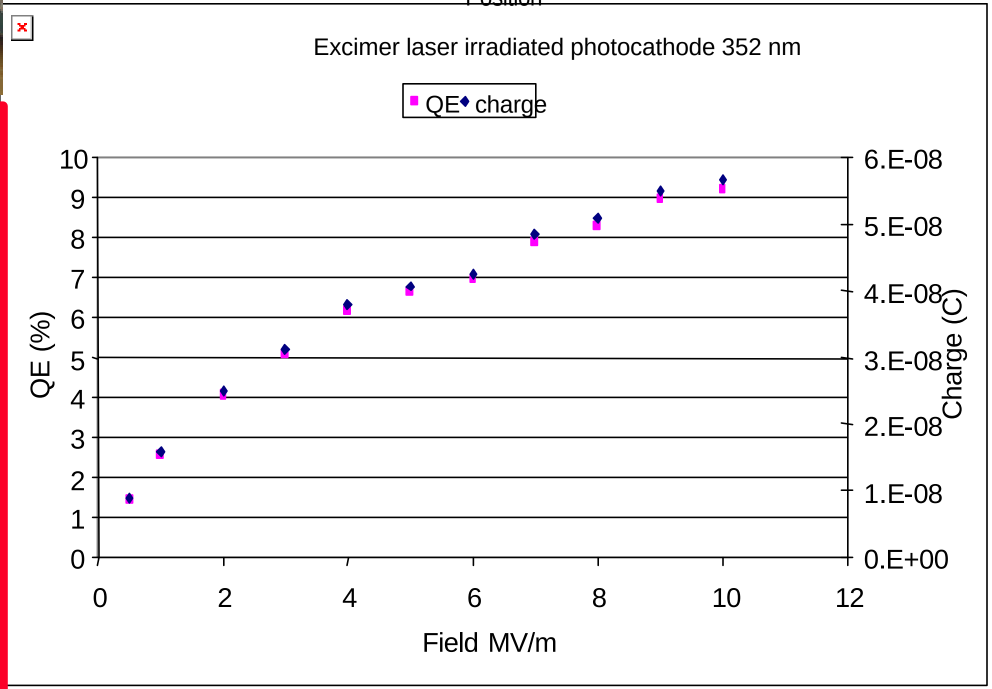
Project	Cathode	Laser	Collaboration	Status
ERL, ecooler	K_2CsSb, Diamond secondary emitter	DPSS laser Shaped beam	CAD, IO, AES, NRL	Ongoing
E RHIC, ILC	Strained GaAs:Cs	Fiber, Ti:Sapp Shaped Beam	CAD, IO, AES, MIT, FNAL	Preliminary

Multialkali Photocathode Development (CAD, IO)

New multialkali cathode deposition and testing system







Results so far:

2 mA delivered with 3% QE @ 532 nm at 81.25 MHz, 10 ps pulse length- space charge limit

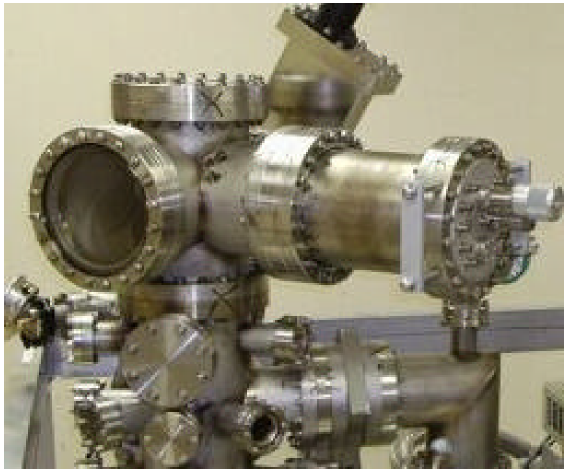
10% QE at 365 nm

Life time > weeks at low 10^{-9} Torr

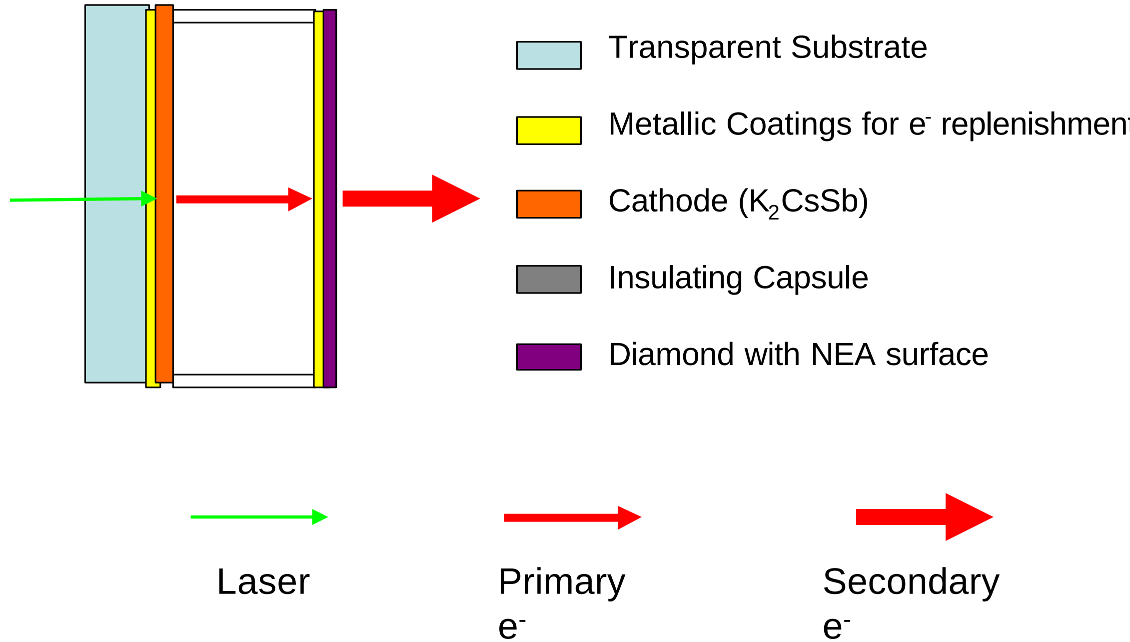
Uniform emission at 545 and 365 nm

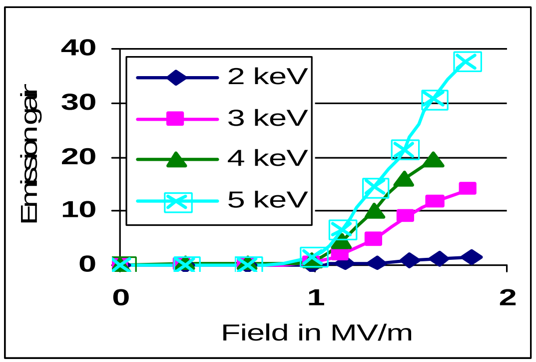
Current density comparable to RHIC II requirement, few days of life time-alignment limit

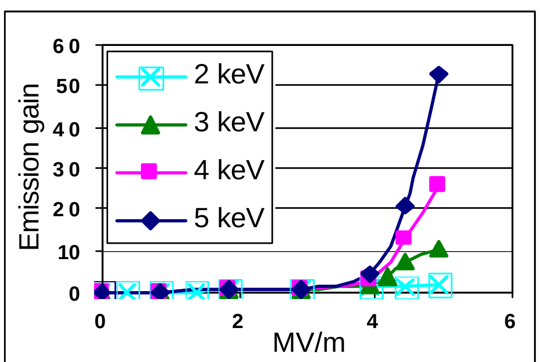
Diamond Secondary Emitter (CAD, IO, NRL)



Diamond Test Chamber







Results so far:

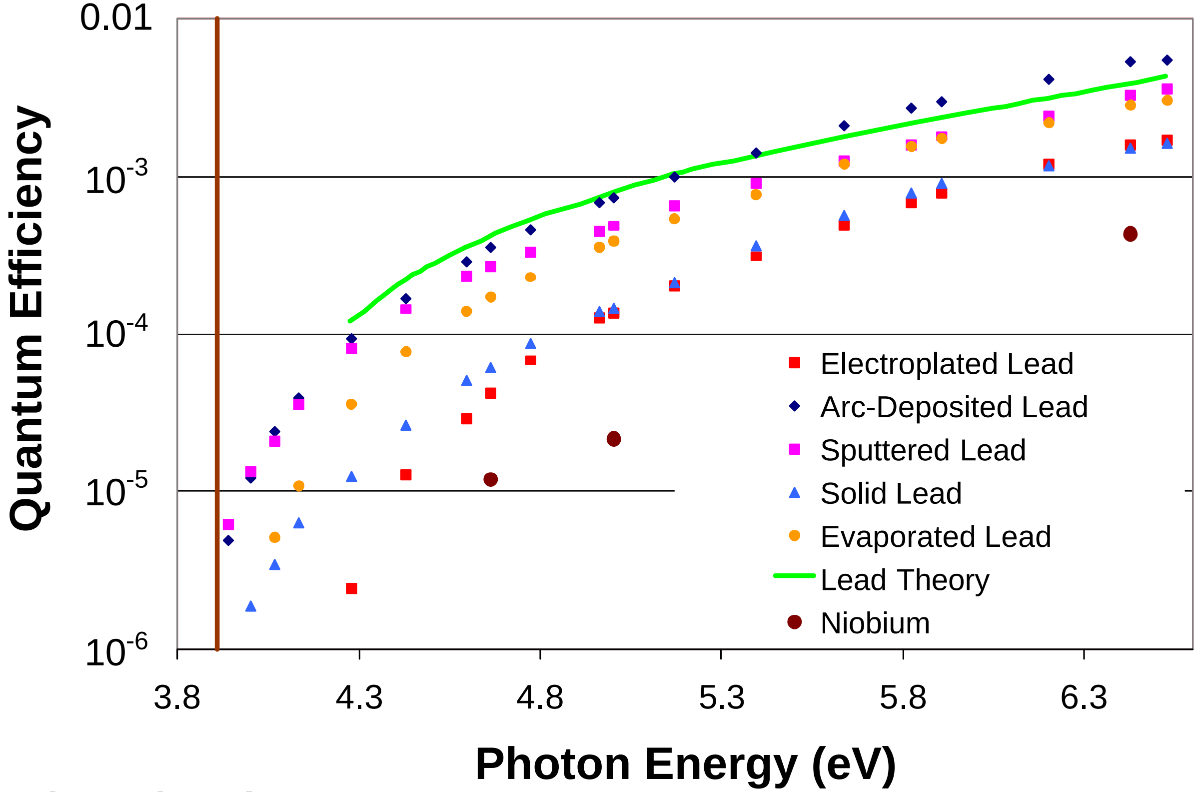
Electron multiplication observed in natural single crystal and CVD polycrystalline diamond in emission mode (gain 50+)

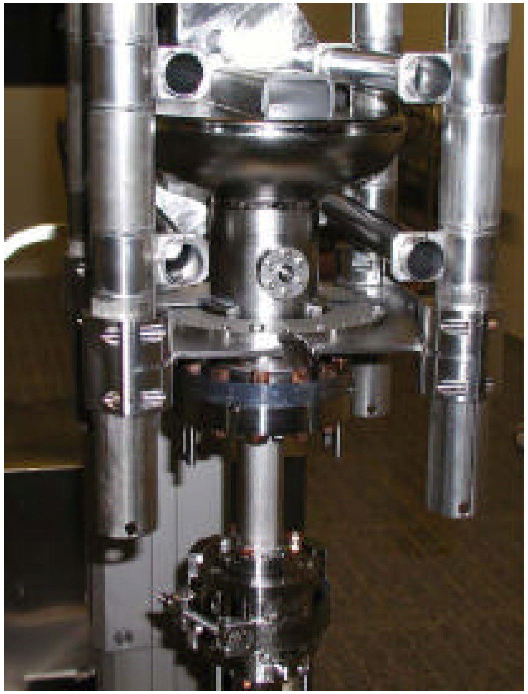
Diamond brazed to Nb

Capsule fabrication in progress

Superconducting *Lead* Photoinjector Development

To improve the Quantum Efficiency of all superconducting photoinjectors. This research may lead to an injector capable of meeting the high average current requirements of tomorrow's LINAC-based Light Sources, such as the DESY X-ray FEL (up to 1nC bunch charge, 1 mA average current, 1 MHz rep. rate).





Niobium cavity prepared for Lead coating

What we have done:

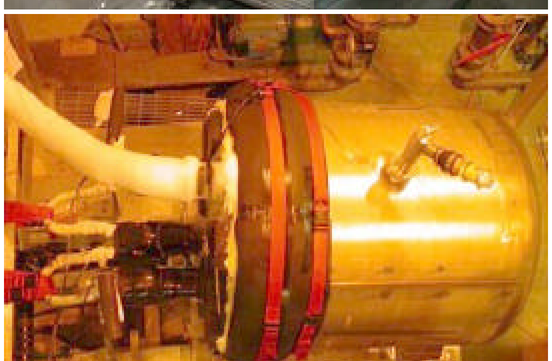
Developed techniques to deposit lead on the cathode region of a niobium superconducting injector. Characterized the QE of these coatings as a function of photon energy. Developed a theoretical model that predicts lead performance. Demonstrated the QE remains stable in cryogenic conditions. Lead has a QE ~8 times that of Niobium, and requires less surface preparation. A niobium cavity has been constructed and will soon have the cathode region coated with lead.

Hg jet target for muon collaboration

BNL-CAP, Princeton
ORNL, MIT, CERN

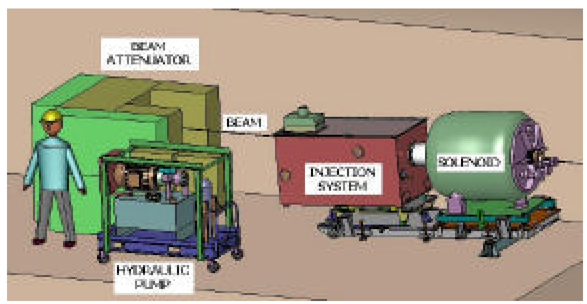
- Proof-of-principle test to demonstrate interaction of Hg jet within a 15 T magnetic field
- CERN facility beam 24 GeV, 1 MW, up to 10^{13} protons/pulse
- Observe beam/jet interaction with high-speed optics, BNL
- Diagnostics: fiber-optic system integrated with high speed camera, BNL

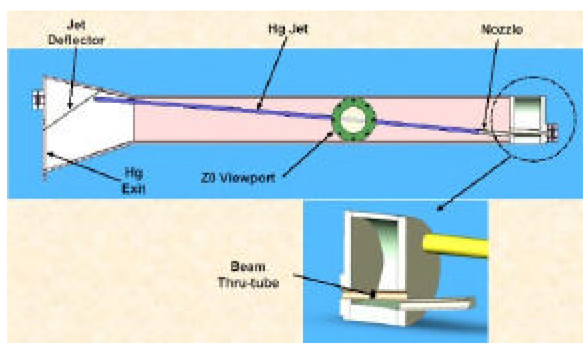
15 T magnet, MIT



15 T achieved at the temp. of 80K

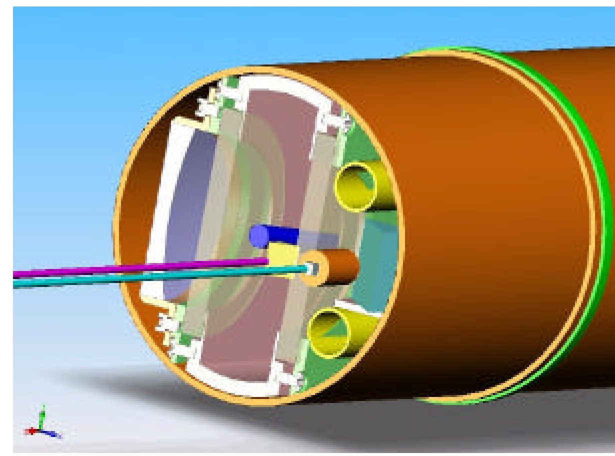
Hg free-jet, ORNL





- system testing at ORNL schedule to begin May 2006

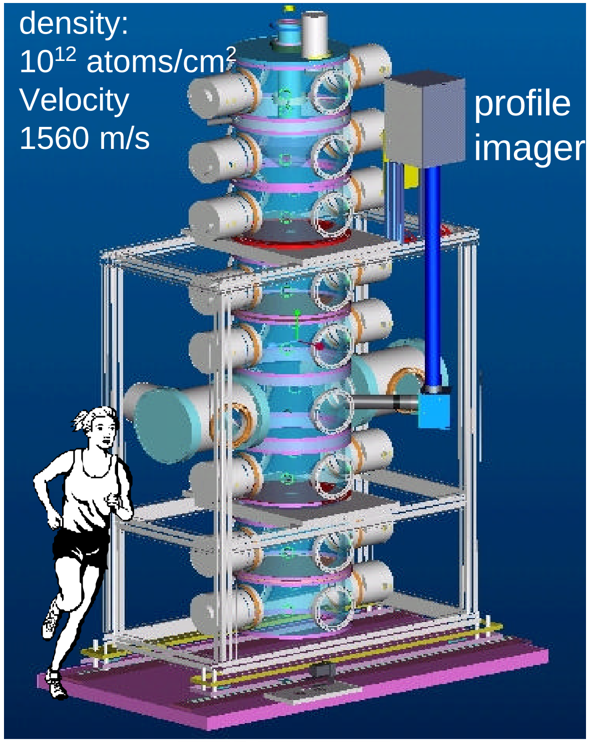
Optical diagnostics, BNL

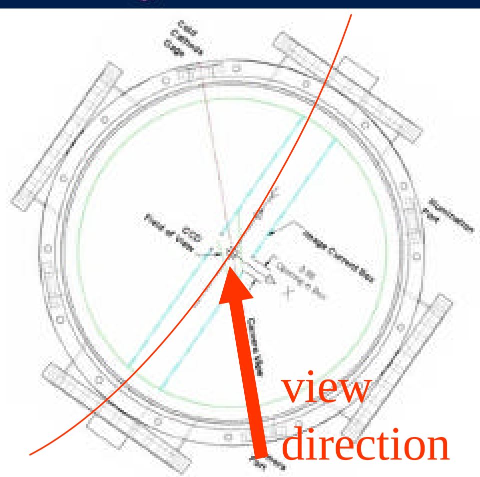


- all passive fiber-optics components
- compact high resolution imaging system
- flexible fiber imaging bundle for imaging transfer, high intensity pulsed laser for illumination
- image capture with 1-μs frame rate CCD
- Beam-on test @ CERN, Dec. 2006

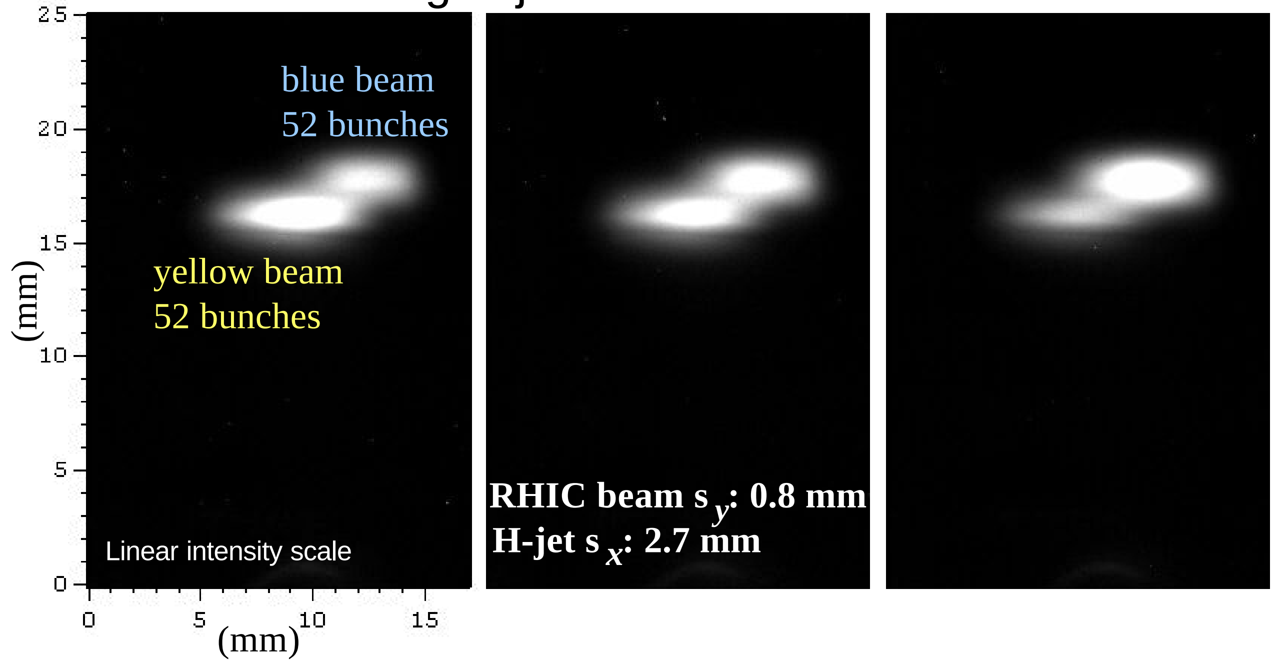
RHIC H-Jet Luminescence Beam Profile Monitor (CAD, IO)

Observe H-a Balmer line emission due to beam hydrogen excitation

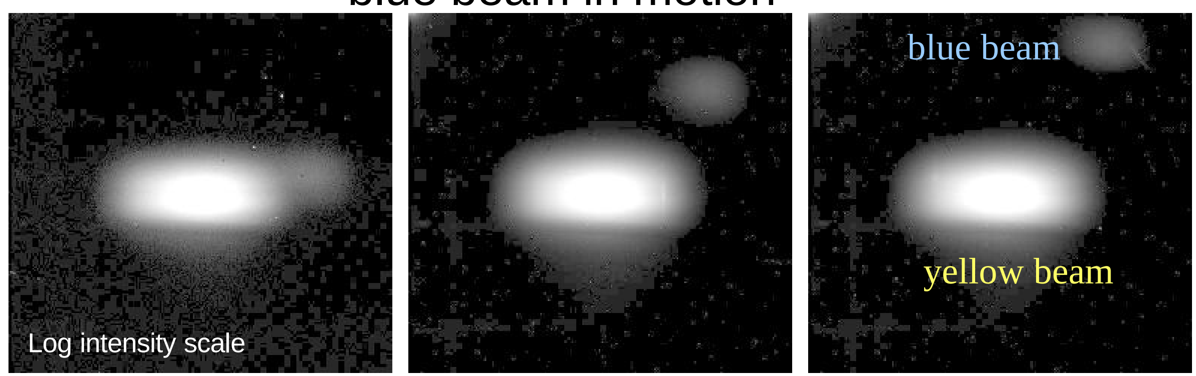




moving H-jet to select RHIC beams



blue beam in motion

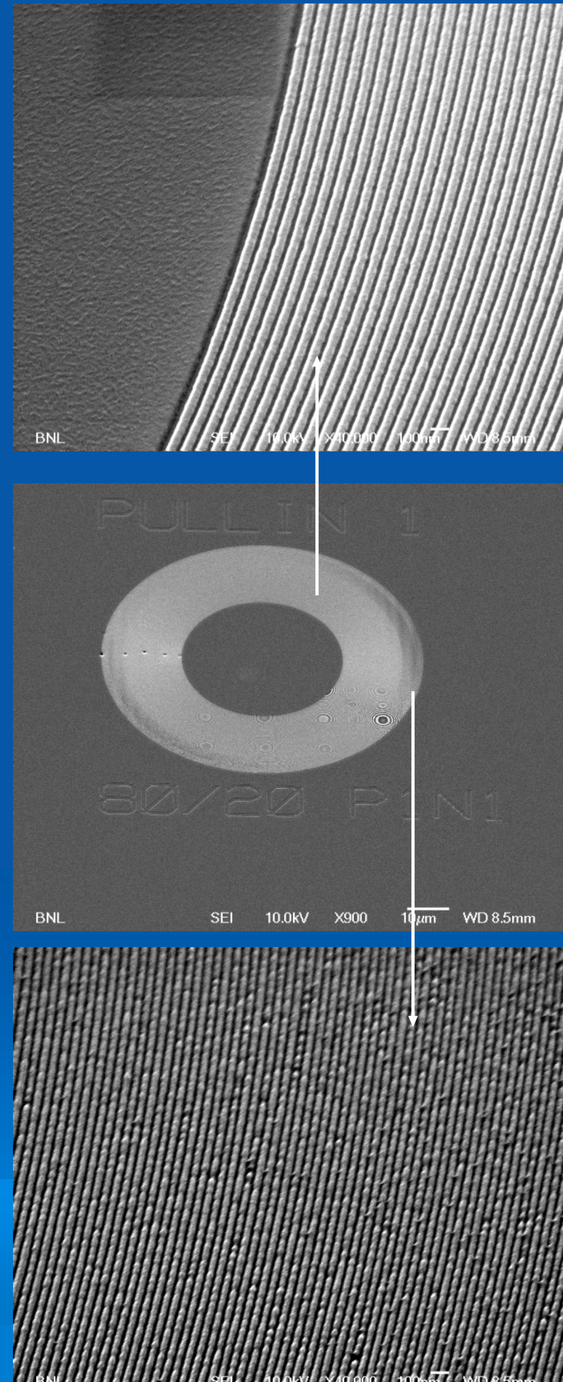


- Beam profile monitor for RHIC
- Detect impurities in the H-jet
- Improve RHIC beam spin polarization measurement

7. Micro/nano Fabrication

X-Ray optics for X1A beamline at the NSLS: Analysis of zone plate patterned on JEOL 9300 at Lucent Technologies and examined by Ming Lu on the *JEOL 6500 high resolution SEM in Instrumentation's Microfabrication Lab.*

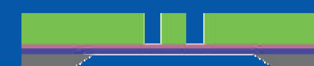
Zones near the outer zone plate diameter show the minimum linewidth achievable with electron beam lithography ~ 20 nm.



Process Steps

E-beam resist exposure

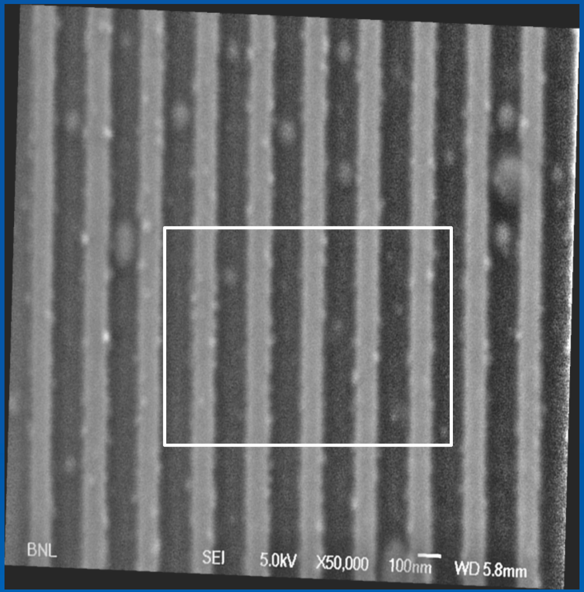
Reactive ion etch of Ge mask

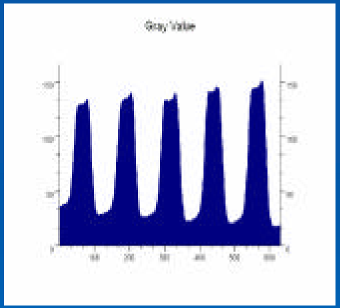


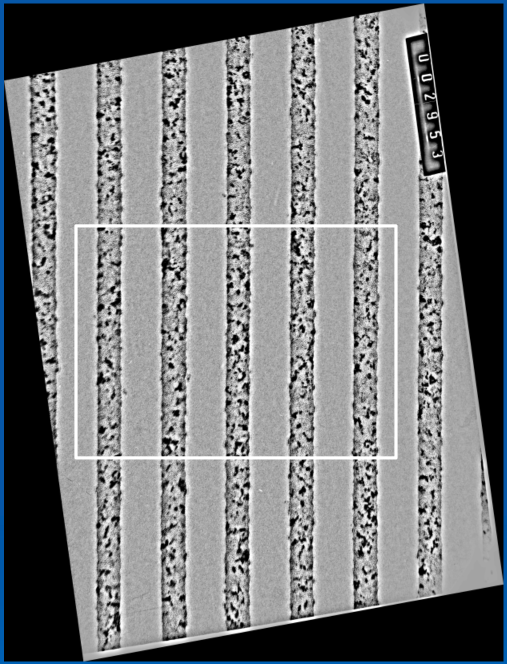
Reactive ion etch of polymer

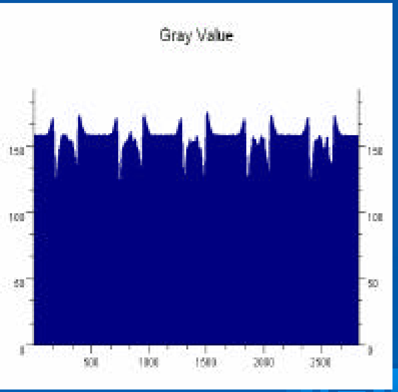
Ni electroplating to form zoneplate

Comparison of line width measurements using *Scanning Electron Microscopy* (*1 – 2 nm resolution*) and *Transmission Electron Microscopy* (*0.2 – 0.4 nm resolution*) of Cr gratings patterned on electron-transparent silicon nitride films









The line width and pitch of nanometer-scale gratings prepared with a JEOL JBX-9300 FS electron beam lithography tool are measured with a JEOL 6500 field emission SEM, and a JEOL 1200 TEM. The JEOL 6500 SEM's resolution is 1.5 nm at 15 keV so TEM methods offer a six-fold potential improvement in resolution over the SEM for metrology. The speckled appearance of the Cr lines in the TEM image is caused by the Bragg condition being satisfied for individual nano-crystalline grains.

Grants for Projects from Diverse Sources

DOE/OBER: **Neutron Detectors; PET**

DOE/BES: **Neutron Detectors**

Other National Labs

- **Los Alamos National Laboratory, "Application Specific Integrated Circuit (ASIC) for Coplanar Grid (CPG) CdZnTe", PI: P. O'Connor**
- **ANL, Neutron Detector, PI: G. Smith**
- **SNS/ORNL, Neutron Detectors, PI: G. Smith**
- **NIST, Neutron Detectors, PI: G. Smith**
- **SLAC, X-ray dets. for Synchrotron Radiation at LCLS**

NRL/DARPA: **x-ray Si Detector for Astrophysics, PI: G. De Geronimo**

CRADAs&Direct Contracts

- **Advanced Energy Systems, PI: T. Srinivasan-Rao**
- **eV Products, Readout ASICs for CZT Detectors, PI: P. O'Connor**

SBIR subcontract

- **Photon Imaging, Readout ASICs for gamma camera, PI: G. De Geronimo**

Work for Others

- **Frequency Electronics Inc., Radiation Effects Testing, J. Kierstead**
- **Advanced Energy Concepts, Si Detector Technology, Z. Li**

Monolithic front-end ASICs under development in Instrumentation for ***astrophysics*** applications

(for NRL, NASA, DARPA, LSST)

- Millisecond pulsar timing, 2 – 30 keV, thick silicon pad detector
- Lunar X-ray fluorescence detector, Si drift detector array
- Solar flare Compton imager
- Low-power CCD signal processor for LSST
- CCD readout ASIC, LSST

Mission *vs* Funding

- Grants from diverse sources are clearly beneficial as they broaden the scope of work and make available the Division's expertise to other institutions. They should be pursued to ***augment*** the base Instrumentation program supported by G&A, and ***they must not detract*** from supporting BNL research program and core technologies.

~30% of the staff funded from other sources.

- Benefit of Instr. Div. to BNL ("and the community at large"):

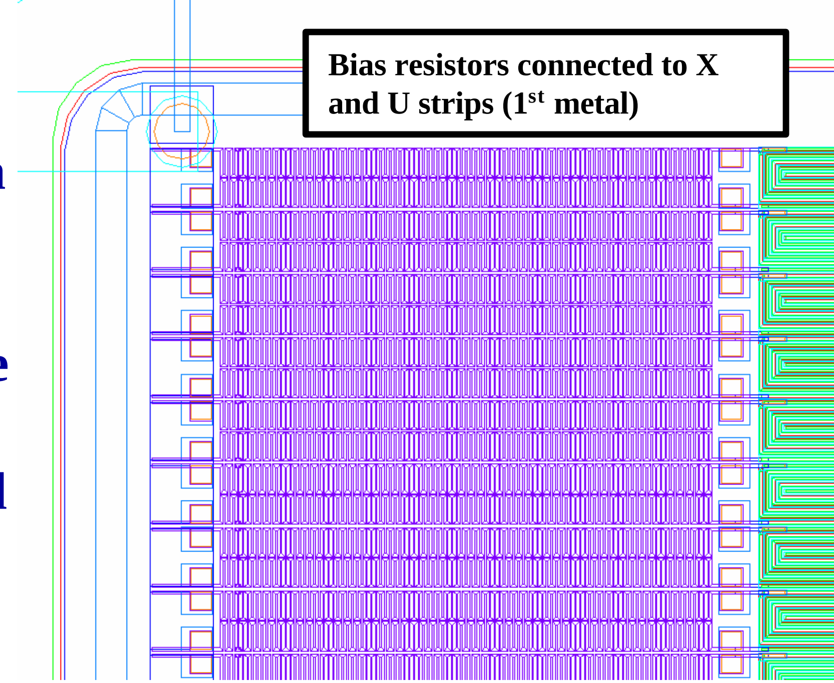
Provide technology base and expertise, and serve as ***a resource for important programs and initiatives***, such as ***RHIC experiments, electron cooling, ATLAS/LHC upgrades, LSST, Linear Collider, as well as for NSLS, detectors at SNS, nanotechnology, and medical imaging***.

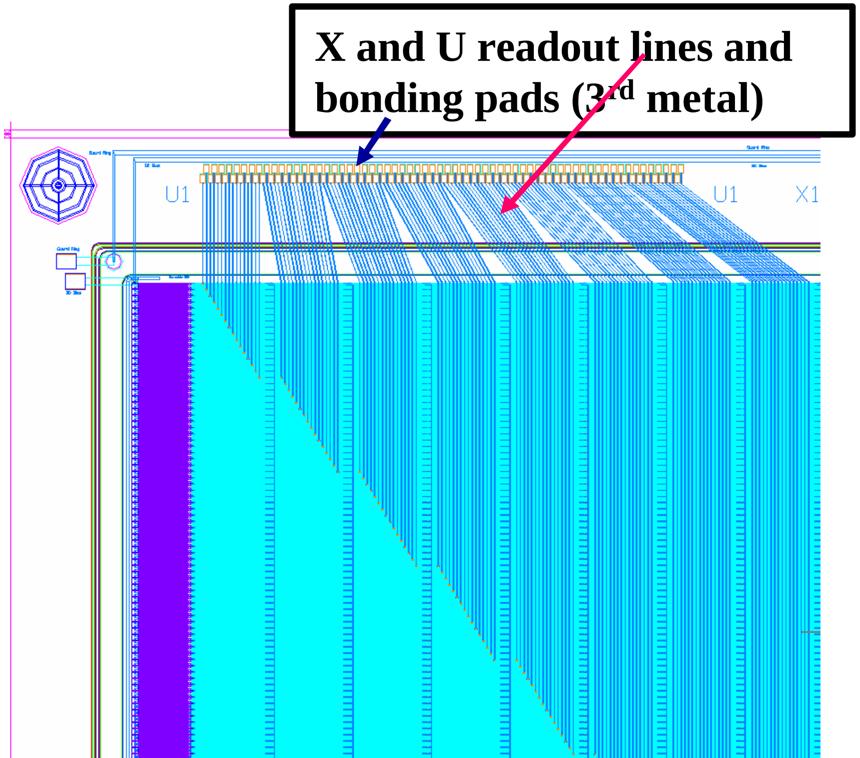
~70% of the staff funded from the Lab overhead (G&A).

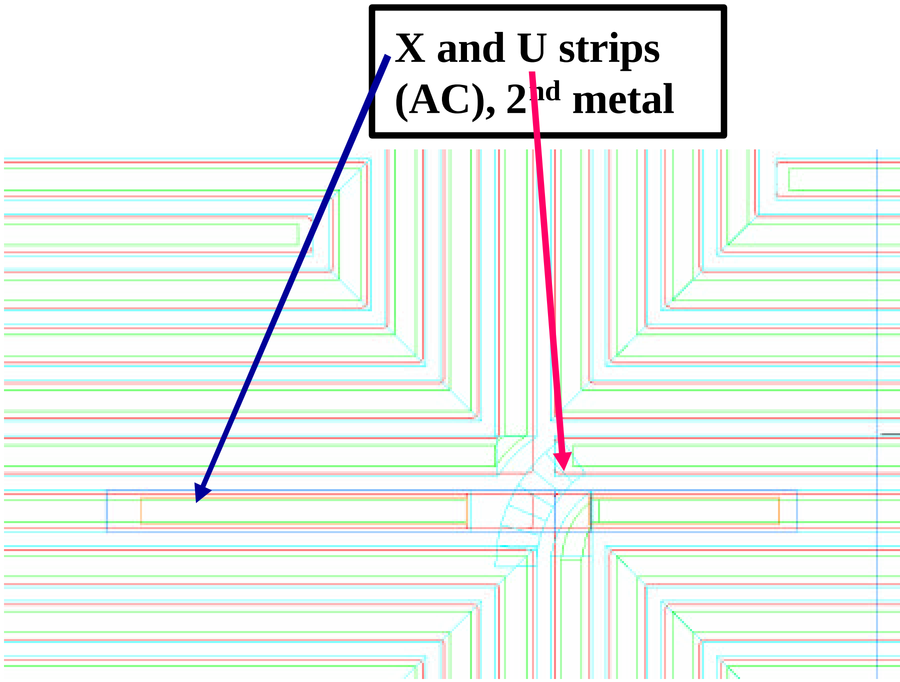
Appendix: Additional Slides

New AC-coupled 2d stripixel detectors for PHENIX Upgrade

1. Intergraded coupling capacitance (insulation between 1st and 2nd metal) and bias resistors
2. Side (perpendicular to strips) readouts as the DC-coupled detectors
3. 3-metal technology (only add one more metal as compared to DC-coupled detectors
4. In R&D phase for contingency purpose

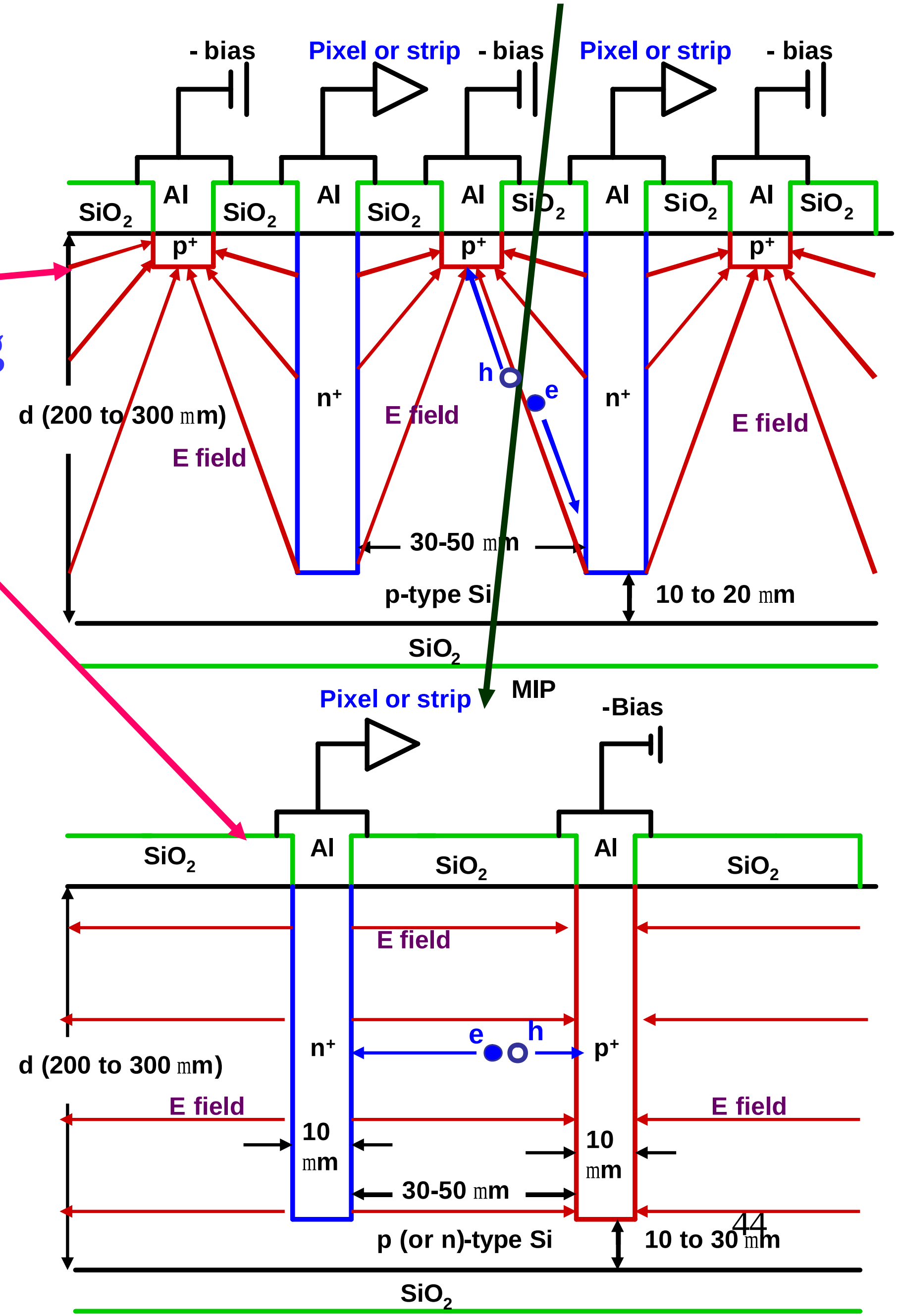






New 3d Structures

- Planar + 3d (we call it P+3d) processing technology
- 1-column and Dual-column etching and doping possible
- True single sided processing (no processing at all on the back side, different from ITC’s 3DSTC detectors)
- Pixel, strip, and 2d stripixel configurations possible depending on electrode connections
- No support wafer

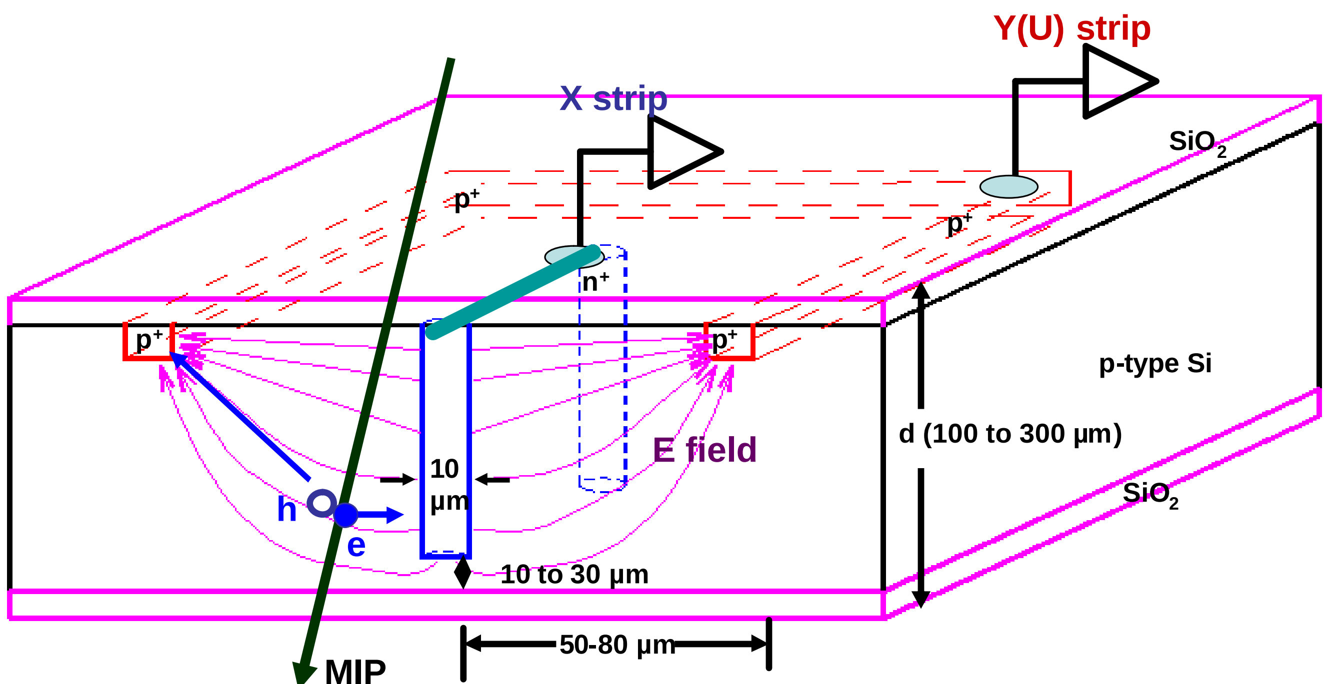


1-column 3d stripixel detectors

1. Partial planar technology
2. No charge sharing problem
3. No added capacitance
4. True one-sided process (no process on the back side at all)
5. 2d-posidition sensitivity
6. Single metal process possible
7. AC coupling possible
8. No SCSI problem (p or n-type bulk)

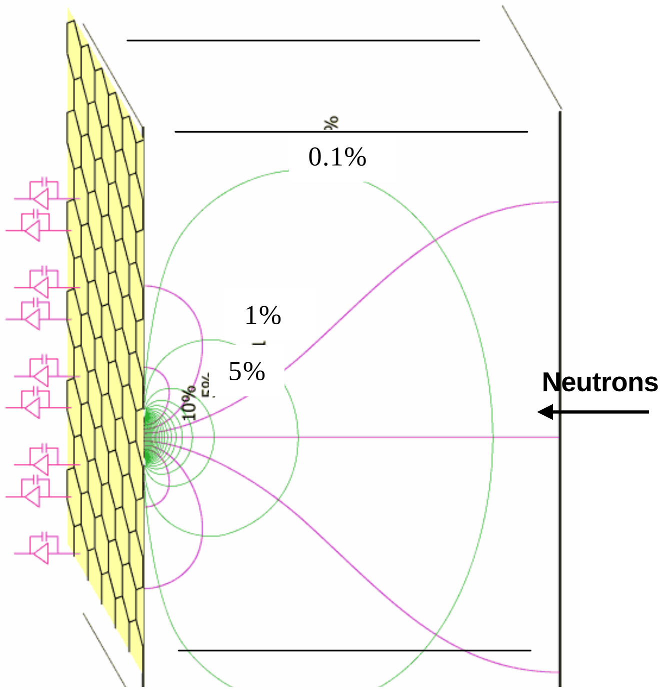
2d in sensing, 3d in processing

- Prototype design has been made
- First batch production has started:
  - CNM of Spain has etched the n+ columns for BNL
  - BNL is now finishing up the remaining planar processing steps
  - 1st prototype detectors will be ready in a couple of months

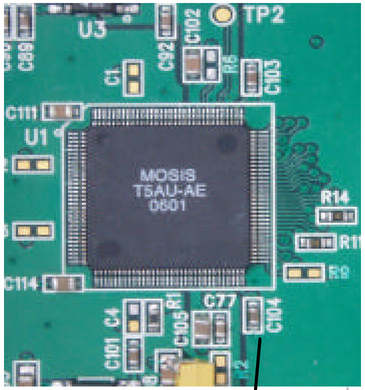


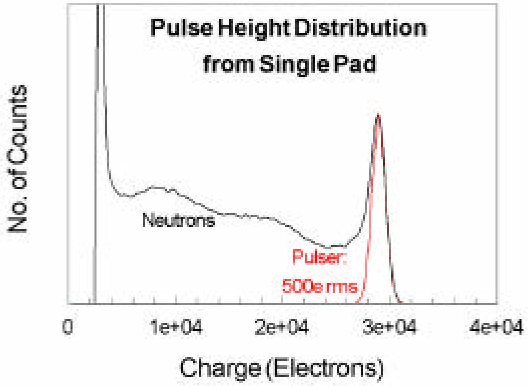
^{3}He Neutron Detector with Unity Gas Gain and Pad-Readout for the SNS – A New Concept

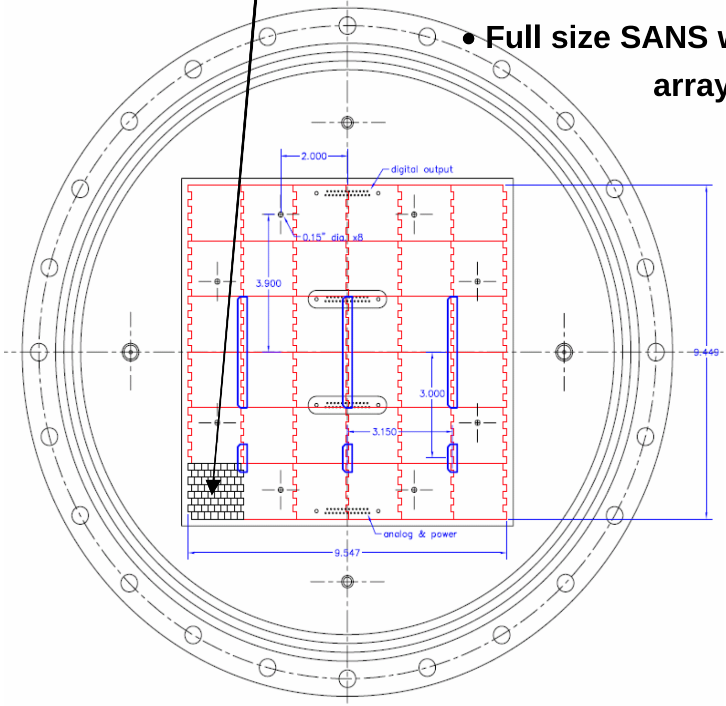
Induced charge detectable on single pad without requiring a Frisch grid



ASIC (on test board) will serve 64 pads



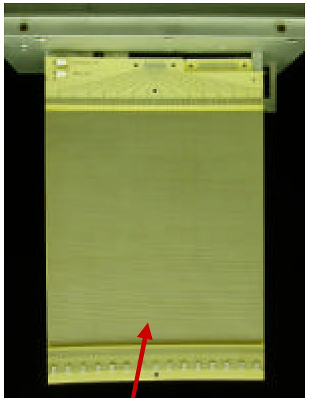




- Collaboration with ORNL, funded by BES
- ***Signal detection with unity gas gain***
- Concept proven with 13 pad array
- Goal is an advanced detector for SANS
- 64 channel ASIC developed (largest die size ever by IO: 6.6´ 8.5 mm^2)
- Current FWP: 48 by 48 pad array development
- Full size SANS will require 196 by 196 pad array (***10^8 n/s***)

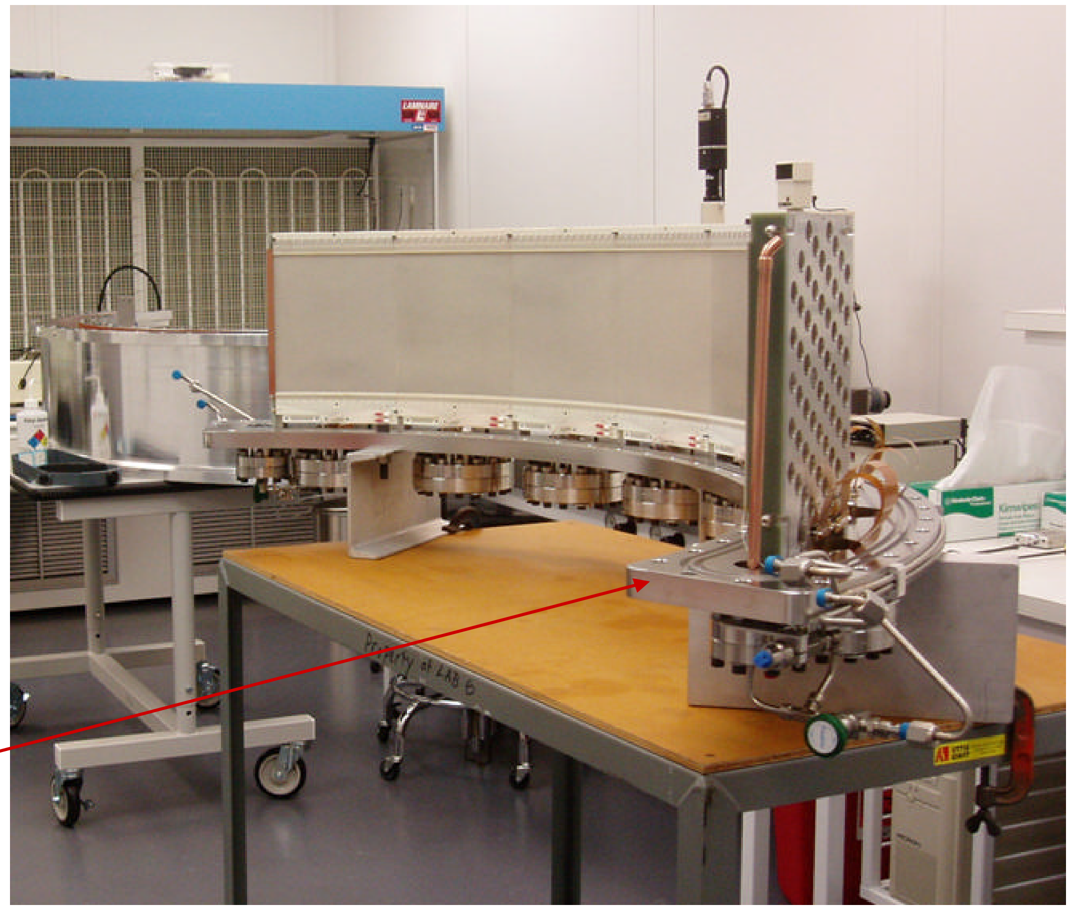
- Design for 48 by 48 array (24cm by 24cm)
- One ASIC per 8 by 8 pad array (bottom left)
- ASICs and much of digital electronics inside gas volume

120° Thermal Neutron Detector for High Intensity Powder Diffractometer (HIPD) at ANSTO, Australia



120x20 cm^2 curved ^{3}He detector. Position information is determined by resistive charge division on multi-node X and Y cathodes, ~***1.3mm FWHM for thermal neutrons***

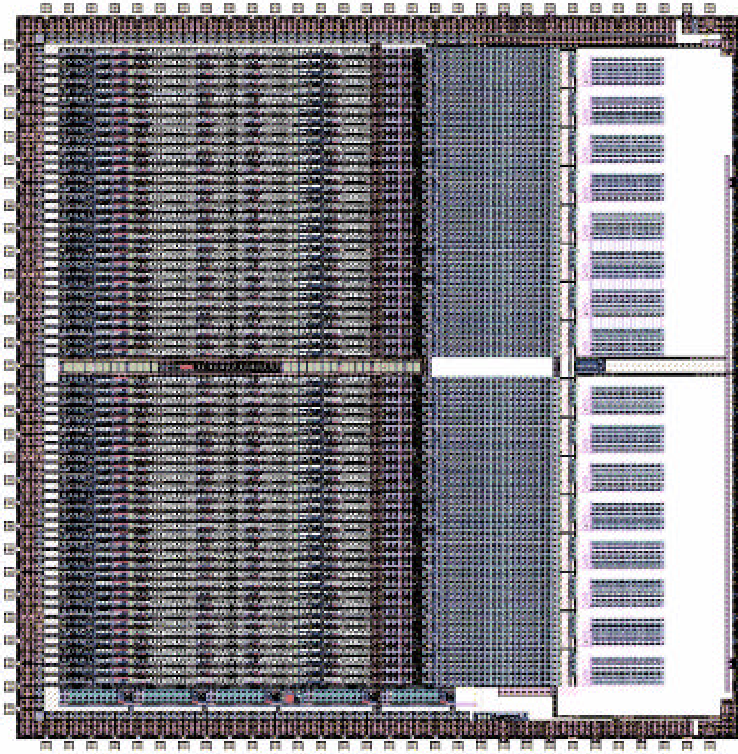
One wire segment is approximately 20cm by 20cm in area, with 120 anode wires.



Eight wire segments mounted on stainless steel flange

The completed detector system, *very similar to the one developed by Instr. Div. for LANSCE four years ago*, will be delivered to *ANSTO* in late summer of 2006 for installation on the HIPD at ANSTO's Replacement Research Reactor (R^3), a new 20MW facility.

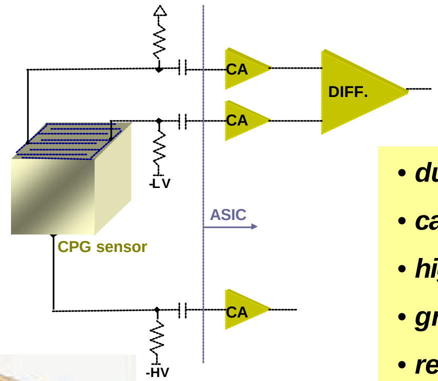
BNL Instrumentation Division – Microelectronics Group

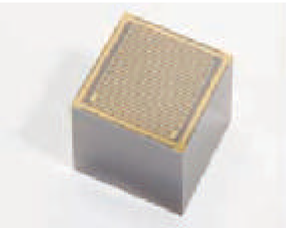


- 4 analog IC designers; 5 engineers
- Specialize in low-noise analog CMOS front ends for radiation detectors
- 7 ASIC designs in use (lab/commercial)
  - Over 70 000 channels
- 5 more in final development
- 3 more to fab in next 6 months
- ***High energy, synchrotron radiation, medical imaging, astrophysics***
- Examples:
  - **ENC=11 e rms**, preamp for Si drift det.
  - Rad-hard preamp/shaper for ATLAS muon spectrometer at LHC
  -- 32-channel PET signal processor

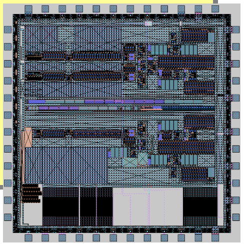
- 64-channel preamp/shaper for hard X-ray spectroscopic imaging
- Front-end + multichannel analyzer per channel
- 600 000 transistors
- concept to tapeout in 3 months

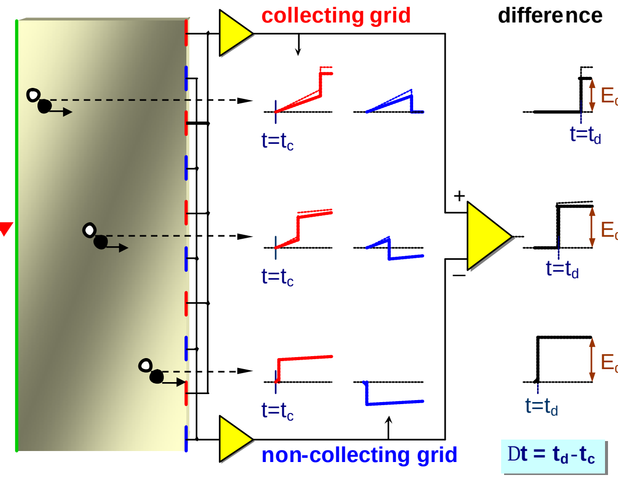
ASIC for Coplanar-Grid CdZnTe Sensors

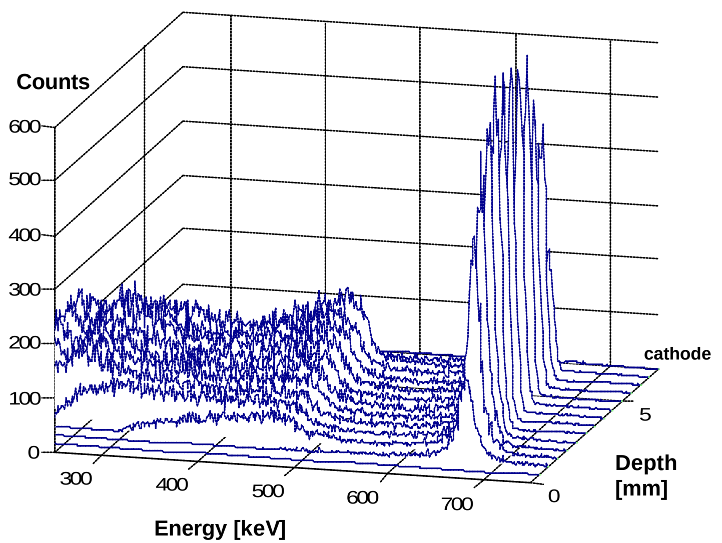


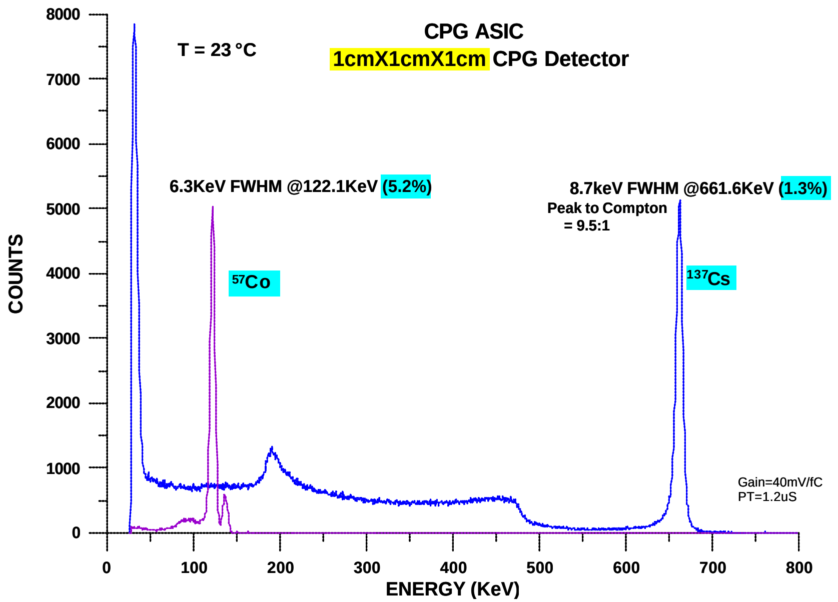


- *dual anode with difference*
- *cathode*
- *high-order filter*
- *grid-only depth-of-interaction measurement*
- *relative-gain compensation*
- *3.1 x 3.1 mm²*
- *2,000 MOSFETs*
- *CMOS 0.25µm technology*





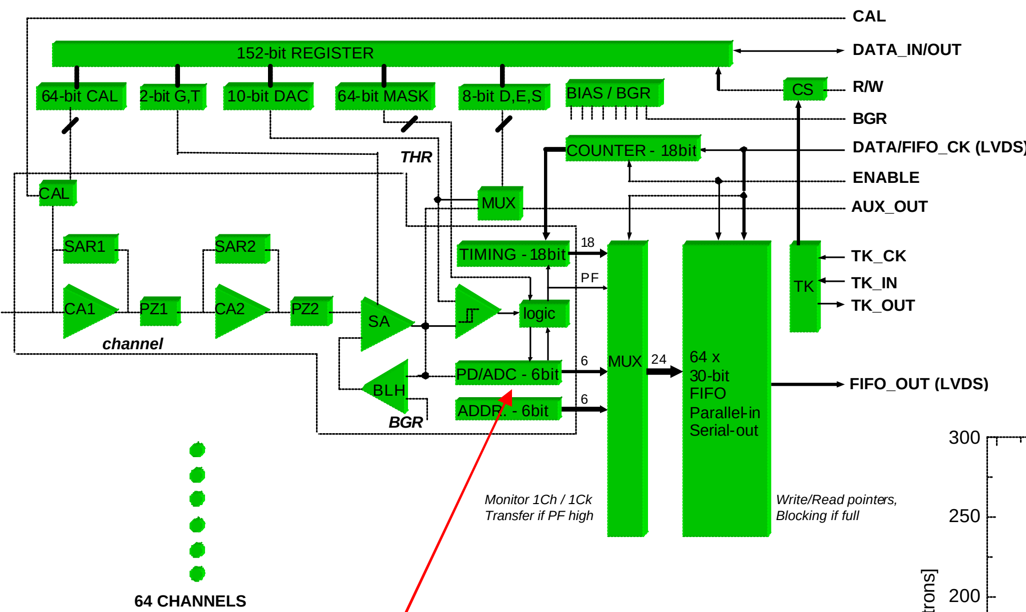


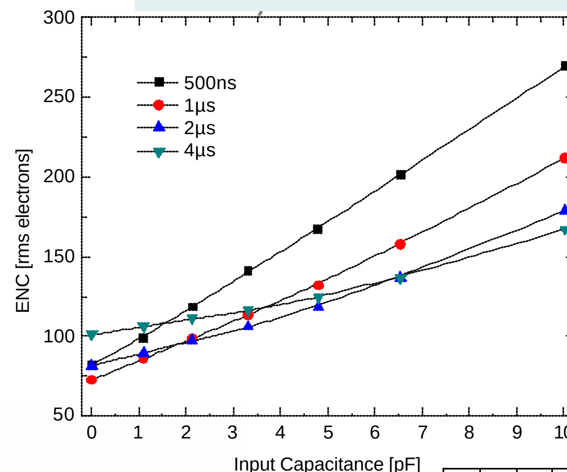


G. De Geronimo, P. O'Connor, G. Carini - W. S, Murray (LANL) - eV Products (PA,USA)

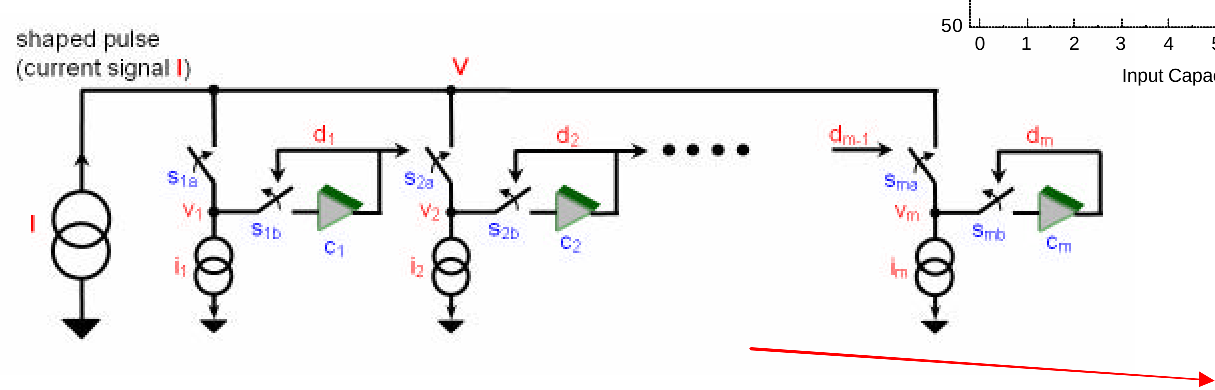
ASIC for Small Angle Neutron Scattering at SNS (ORNL)

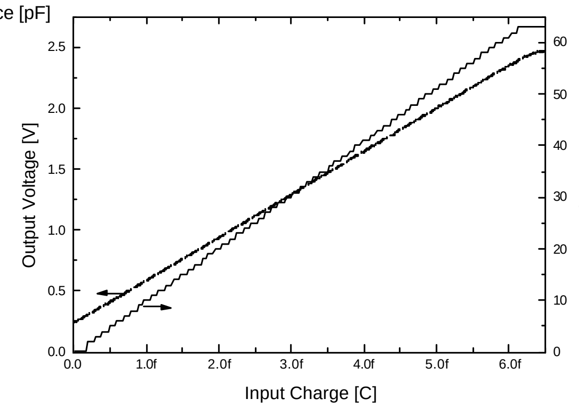
- 64 channels, each with:
  - preamplifier
  - 3rd order shaper 500ns-4µs
  - gain 350mV / fC
  - 6-bit peak-detector ADC
  - 18-bit timestamp
- multiplexing to 64x30-bit FIFO
- LVDS inputs/outputs
- analog monitors with output buffer
- 0.25µm CMOS, 5 mW/channel
- **315,000 MOSFETs in 6.6 x 8.5 mm²**





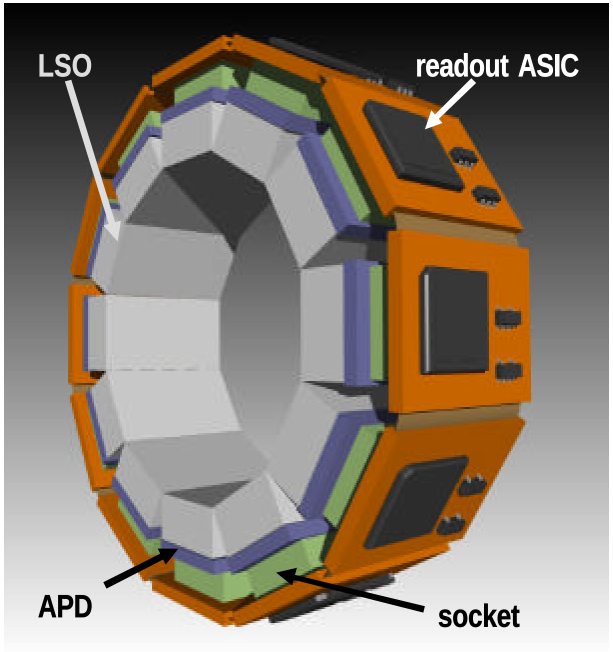
Current-mode low-power peak-detector ADC



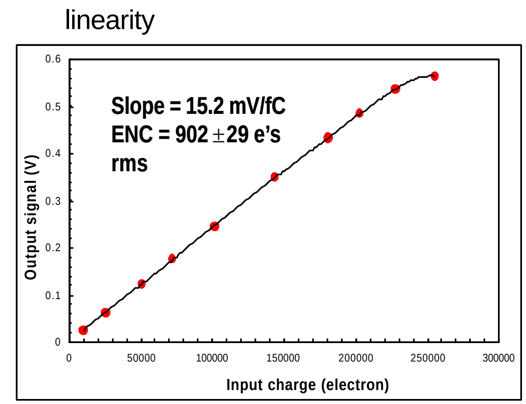


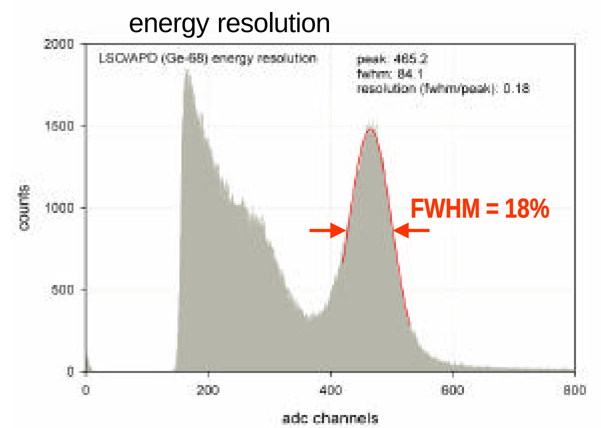
G. De Geronimo - ORNL

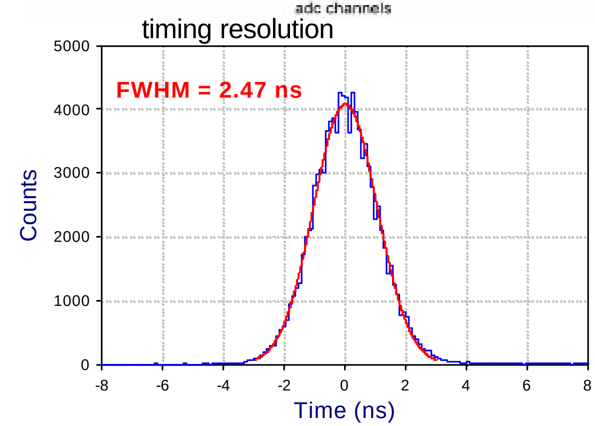
Electronics for a mobile, miniature animal PET tomograph



- **0.18 µm CMOS**
- 1.5 mW/channel
- 32 channel ASIC
- Preamplifier + shaper + timing discriminator
- serialized output

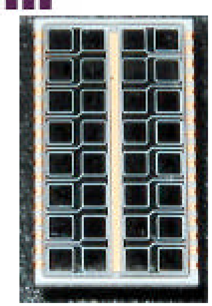






Mockup of the portable ring on the head of a rat

LSO scintillator



APD array

ASIC preamplifier with CFD vs. BaF_2/PMT

ASICs Developed at the Instrumentation Division During the Past 6 Years

from design-start to ready-for-production

YEAR	FUNCTION	APPLICATION	COOPERATION	TECHNOLOGY	CHAN. NUMBER	TRANS. COUNT	DEVEL. TIME [months]
2000	Front-End for CZT	General Purpose	eV Products	CMOS 0.50µm	4-16	4-16,000	30
2000	Multiplexing	General Purpose	eV Products	CMOS 0.50µm	32:1	16,000	18
2001	Front-End	ATLAS	BNL	CMOS 0.50µm	25	10,000	96
2001	Multiplexer	ATLAS	BNL	CMOS 0.50µm	24:4	2000	6
2002	Clock Fanout	ATLAS	BNL	CMOS 0.50µm	4:6	100	1
2003	Front-End Counting for Silicon	NSLS	NSLS/BNL	CMOS 0.35µm	32	180,000	30
2003	Front-End Energy/Timing for GEM	TPC	LEGS/BNL	CMOS 0.25µm	32	40,000	16
2004	Front-End Energy for CPG	Security/Safety	LANL, eV Products	CMOS 0.25µm	3	2,000	16
2004	Peak/Timing Processor Multiplexer	General Purpose	eV Producst, NSLS	CMOS 0.35µm	32:1	36,000	24
2004	Front-End Counting for Si-Scint.	Medical	Digirad	CMOS 0.35µm	32	200,000	6
2004	Front-End for APD	Small Animal PET	BNL	CMOS 0.18µm	32	15,000	42 (in prog., v.2)
2005	Front-End Counting for CZT	Industrial	eV Products	CMOS 0.25µm	64	601,000	16 (in prog., v.2)
2005	Front-End Energy and Timing for Gas	Small Angle Neutron Scattering at SNS	BNL,ORNL	CMOS 0.25µm	64	315,000	14 (in prog., v.2)
2005	Front-End Energy for Si	Space - X-Ray Navigator	BNL,NRL	CMOS 0.25µm	36	42,000	13 (in prog.)
2006	Front-End Energy for Si	Space - Lunar Surveyor	BNL, NASA	CMOS 0.25µm	14	n.a.	1 (in prog.)
2006	Sensor + Front-End (APS)	Charged Particle Tracking, Electron Microscopy	BNL (LDRD)	CMOS 0.25µm	n.a.	n.a.	0.5 (in prog.)
2006	Front-End Energy for Si	Space - Solar Flare Compton Imager	BNL, NRL	CMOS 0.25µm	n.a.	n.a.	0.5 (in prog.)
2006	Front-End Energy for CZT	High Resolution Spectroscopy	BNL, Univ. of Michigan	CMOS 0.25µm	n.a.	n.a.	0.5 (in prog.)

Updated April 2006